Wyoming Water Research Program
Annual Technical Report
FY 2009

Introduction

The NIWR/State of Wyoming Water Research Program (WRP) coordinates participation in the NIWR program through the University of Wyoming Office of Water Programs (OWP). The primary purposes of the WRP are to support and coordinate research relative to important water resources problems of the State and Region, support the training of scientists in relevant water resource fields, and promote the dissemination and application of the results of water-related research. In addition to administrating the WRP, the Director of the OWP serves as the University of Wyoming advisor to the Wyoming Water Development Commission (WWDC).

State support for the WRP includes direct funding through the WWDC and active State participation in identifying research needs and project selection and oversight. Primary participants in the WRP are the USGS, the WWDC, and the University of Wyoming. A Priority and Selection Committee (P&S Committee), consisting of representatives from agencies involved in water related activities in the State, solicits and identifies research needs, selects projects, and reviews and monitors project progress. The Director of the OWP serves as a point of coordination for all activities and serves to encourage research by the University of Wyoming addressing the needs identified by the P&S Committee. The State provides direct WWDC funding for the OWP, which was approved by the 2002 Wyoming Legislature, to identify water related research needs, coordinate research activities, coordinate the Wyoming WRP, and serve as the University advisor to the WWDC.

The WRP supports faculty and students in University of Wyoming academic departments. Faculty acquire their funding through competitive, peer reviewed grants, submitted to the WRP. Since its inception in the year 2000, the WRP has funded a wide array of water related projects across several academic departments.

Research Program Introduction

Since inception of the NIWR program in 1965, the Wyoming designated program participant has been the University of Wyoming. Until 1998, the Wyoming NIWR program was housed in the Wyoming Water Resources Center (WWRC). However, in 1998 the WWRC was closed. In late 1999, the Wyoming Water Research Program (WRP) was initiated to oversee the coordination of the Wyoming participation in the NIWR program. The primary purpose of the Wyoming Institute beginning with FY00 has been to identify and support water-related research and education. The WRP supports research and education by existing academic departments rather than performing research in-house. Faculty acquire funding through competitive, peer reviewed proposals. A goal of the WRP is to minimize administrative overhead while maximizing the funding allocated toward water-related research and training. Another goal of the program is to promote coordination between the University, State, and Federal agency personnel. The WRP provides interaction from all the groups involved rather than being solely a University of Wyoming research program.

In conjunction with the WRP, an Office of Water Programs was established by State Legislative action beginning July 2002. The duties of the Office are specified by the legislation as: (1) to work directly with the director of the Wyoming water development office to identify research needs of state and federal agencies regarding Wyoming water resources, including funding under the National Institutes of Water Resources (NIWR), (2) to serve as a point of coordination for and to encourage research activities by the University of Wyoming to address research needs, and (3) to submit a report annually prior to each legislative session to the Select Water Committee and the Wyoming Water Development Commission on the activities of the office.

The Wyoming Water Research Program (WRP) is a cooperative Federal, State, and University effort. All activities reported herein are in response to the NIWR program, with matching funds provided by the Wyoming Water Development Commission and the University of Wyoming. While the WRP is physically housed in the Engineering College, the Director reports to the University of Wyoming Vice President of Research and Economic Development. A State Advisory Committee (entitled the Priority and Selection Committee) serves to identify research priorities and select projects for funding. The Director coordinates all activities.

Reports for nine research projects are given herein. In addition to the nine FY09 active projects, the Wyoming Institute is currently supporting seven new research projects which were initiated March 2010. The seven new projects are listed below, but annual reports are not included herein. The seven new projects were selected by the Institute Advisory Committee based upon peer reviews and subsequent ranking by the Advisory Committee of proposals received in response to the Institute FY10 RFP.

Reports presented herein (listed in order of presentation) are: (1) Final Report: Real-Time Monitoring of E. Coli Contamination in Wyoming Surface Waters; (2) Final Report: Integrated Management of Groundwater and Surface Water Resources: Investigation of Different Management Strategies and Testing in a Modeling Framework, Fred Ogden, Civil and Architectural Engr., and Melinda H. Benson, Ruckleshaus Institute of Environment and Natural Resources (formerly), UW, Mar 07 thru Feb 10; (3) Final Report: Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstroms in Wyoming Using the Wyoming Cloud Radar, Bart Geerts, Dept. of Atmospheric Science, UW, Mar 07 thru Feb 10; (4) Final Report: Weather Modification Impacts and Forecasting of Streamflow, Glenn Tootle, Civil and Architectural Engr., UW and Tom Piechota, Univ. of Nevada. Mar 07 thru Feb 10; (5) Final Report: A New Method for Tracing Seepage from CBNG Water Holding Ponds in the Powder River Basin, Wyoming, Shikha Sharma and K.J. Reddy, Dept. of Renewable Resources, UW, and Carol Frost, Dept. of Geology and Geophysics, UW, Mar 08 thru Feb 10; (6) Annual Report: Water Quality Criteria for Wyoming Livestock and Wildlife, Merl Raisbeck, Dept Veterinary Sciences; Cynthia Tate, Wyoming Game & Fish Dept; and Michael Smith, Dept of Renewable Resources, UW, Mar 08 thru Feb 11; (7) Annual Report: Detecting the Signature of Glaciogenic Cloud

Seeding in Orographic Snowstorms in Wyoming II: Further Airborne Cloud Radar and Lidar Measurements, Bart Geerts, Dept of Atmospheric Science, UW, Mar 09 thru Feb 12; (8) Annual Report: Effects of Warm CBM Product Water Discharge on Winter Fluvial and Ice Processes in the Powder River Basin, Robert Ettema, Engineering and Applied Science, and Edward Kempema, Dept of Geology and Geophysics, UW, Mar 09 thru Feb 11; and (9) Annual Report: Characterization of Algal Blooms Affecting Wyoming Irrigation Infrastructure: Microbiological Groundwork for Effective Management, Naomi Ward, and Blaire Steven, Dept of Molecular Biology, UW, Mar 09 thru Feb 11.

New Projects (as of March 2010) are: (1) Is the Muddy Creek food web affected by coalbed natural gas inputs?, Lusha Tronstad, Research Scientist, and Wendy Estes-Zumpf, Research Scientist Wyoming Natural Diversity Database, UW, Mar 10 thru Feb 11; (2) Using Voluntary Arrangements to Reduce Diversions and Improve Stream Flows for In-channel Benefits in Wyoming, Lawrence J. MacDonnell, Professor of Law, University of Wyoming College of Law, Mar 10 thru Feb 11; (3) Development of a Contaminant Leaching Model for Aquifer Storage and Recovery Technology, Maohong Fan, SER Associate Professor, Dept. of Chemical & Petroleum Engineering, UW, Mar 10 thru Feb 12; (4) Development of GIS-based Tools and High-Resolution Mapping for Consumptive Water Use for the State of Wyoming, Gi-Hyeon Park, Assistant Prof. and Mohan Reddy Junna, Prof., Dept. of Civil and Architectural Engineering, UW, Mar 10 thru Feb 12; (5) Treatment of High-Sulfate Water used for Livestock Production Systems, Kristi M. Cammack, Ph.D., Assistant Professor, and Kathy J. Austin, M.S., Senior Research Scientist, Dept. of Animal Science, UW, and Ken C. Olson, Associate Professor, West River Ag Center, South Dakota State University, Rapid City, SD, and Cody L. Wright, Associate Prof., Dept. of Animal and Range Sciences, South Dakota State University, Brookings, SD, Mar 10 thru Feb 12; (6) Multi-Century Droughts in Wyomings Headwaters: Evidence from Lake Sediments, Bryan N. Shuman, Associate Prof., Dept. of Geology & Geophysics, Jacqueline J. Shinker, Assistant Prof., Dept. of Geography, Thomas A. Minckley, Assistant Prof., Dept. of Botany, UW, Mar 10 thru Feb 13; and (7) Impact of bark beetle outbreaks on forest water yield in southern Wyoming, Brent E. Ewers, Assoc. Prof., Dept. of Botany, Elise Pendall, Assoc. Prof., Dept. of Botany, and David G. Williams, Prof., Dept. of Renewable Resources, UW, Mar 10 thru Feb 13.

Real-Time Monitoring of E. Coli Contamination in Wyoming

Basic Information

Title:	Real-Time Monitoring of E. Coli Contamination in Wyoming
Project Number:	2005WY24B
Start Date:	3/1/2005
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Water Quality, Methods, None
Descriptors:	
Principal Investigators:	Paul E. Johnson

Publications

1. Johnson, P.E., A.J. Deromedi, P. Lebaron, P. Catala, and J. Cash, 2006. Rapid detection and enumeration of Escherichia coli in aqueous samples using Fountain Flow Cytometry, Cytometry, 69A, 1212-1221.
2. Johnson, P.E., Deromedi, A.J., Lebaron, P., Catala, P., Havens, C., and Pougnard, C. 2007. High Throughput, Real-time Detection of Naegleria Lovaniensis in Natural River Water Using LED-Illuminated Fountain Flow Cytometry, J Appl Microbiol. 103 (3), 700 710.
3. Jean-Baptiste Fini, Sophie Pallud-Mothr , S bastien Le M vel, Karima Palmier, Christopher M. Havens, Matthieu Le Brun, Vincent Mataix, Gregory F. Lemkine, Barbara A. Demeneix, Nathalie Turque and Paul E. Johnson, 2009. An Innovative Continuous Flow System for Monitoring Heavy Metal Pollution in Water Using Transgenic Xenopus laevis Tadpoles, Environmental Science and Technology, 43(23), pp 8895-8900.

Real-Time Monitoring of E. Coli Contamination in Wyoming Surface Waters

PI: Dr. Paul E. Johnson, Physics and Astronomy, University of Wyoming

Final report for a three-year project: March 05 – February 08

Abstract

This project shows the feasibility of economical, simultaneous, real-time detection of individual *Escherichia coli* and their viability in surface waters. The Clean Water Act requires states to monitor surface waters for fecal coliforms or specifically for *E. coli*. Fecal coliform monitoring is an indicator of the sanitary quality of the water and can determine the extent of fecal contamination in the water from warm-blooded animals. A low-cost, portable, highly sensitive, self-contained single cell detection prototype for *E. coli* enumeration was developed for rapid monitoring of surface waters, including streams, rivers, and lakes. With USGS/WWDC funding, the P-I and his team have demonstrated and significantly improved an innovative technique for detection of pathogenic microorganisms in surface water, economically and in real time. This technology is based on LED-induced fluorescence of antibody- and DNA labeled cells. *The project demonstrated the detection of individual E. coli simultaneously in two wavebands in order to detect and determine viability of individual microorganisms.* The suspended bacteria are stained using both an immunofluorescent antibody and a fluorescent cell viability label. The resulting aqueous sample is passed as a stream in front of an LED, which excites the fluorescent labels (Figures 1 and 2). The resulting fluorescence is measured with a CCD or CMOS imager using an innovative integration scheme (called *Fountain Flow*), giving a dramatically higher signal-to-noise ratio than conventional techniques. In addition, we are investigating the extension of the fountain flow technology to imaging, to provide increased discrimination capability among *E. coli*, other biological particles, and small geological particles.

Objectives

The major tasks of this 3-year project were to: 1.) fabricate and test a two-color, LED-illuminated detection system in order to simultaneously detect and determine the viability of *E. coli*, 2.) perform laboratory measurements on quantified *E. coli* samples to determine the detection efficiency and sensitivity of the two-color monitoring system, 3.) enumerate *E. coli* in stream and lake water samples using both our proposed method and the standard method currently recommended by the US Environmental Protection Agency, and 4.) determine the feasibility of a rare-cell, fountain flow *imaging* system based on an extension of our current technology, and 4.) fabricate and test a prototype fountain flow imaging system for proof of concept.

Final Progress Report, 3 Years of Funding

Summary

We completed and tested improvements on a low-cost, portable, highly sensitive, self-contained single-cell detection system for *E. coli* in surface waters, which greatly exceeds the current testing procedures in both speed and reliability. The goal of this project was the development of 1) a low-cost, rapid (<< 1 hour test), sensitive (< 5 cells/ml), portable, easy to use system for *E. coli* detection in raw surface water. Our objectives were to: 1) develop and test a system for simultaneous detection and viability testing of *E. coli* and 2) develop and test a proof- of-concept prototype for multi-spectral high resolution FF imaging. We completed the first objective, and the second is still being pursued, although limited funding precludes us finishing that in a timely way. This proof of concept will allow for the design and fabrication of a remote monitoring system that will automatically screen water in real time. Alternative methods necessitate the shipping of bulk water samples or concentrates to laboratories and labor-intensive screening technologies, which may include bulk water concentration, incubation, and culturing. These factors combine to impede overall routine monitoring for fecal coliforms in the field and preclude widespread, routine screening of surface waters.

Over the three-years of funding, we have:

- successfully fabricated a two-color detection system for detection of microorganisms,
- continued successful proof of concept experiments for a fountain flow (FF) imaging system, using a syringe pump to consistently stop fluorescent beads in the focal plane of the FFC,
- collected data on the two-color detection of amoebae in natural river water for a manuscript to be submitted this year,
- published a paper on the detection of *E. coli* in water to the journal Cytometry,
- published a paper on the detection of amoebae in natural river water using LED illumination, against a background of organic detritus, in the Journal of Applied Microbiology,
- published a paper on the detection of heavy metal contamination in water using tadpoles (in Environmental Science and Technology, 2009) shown in the YouTube video http://www.youtube.com/watch?v=BPpUyYAINdI , and
- have pending patent applications for the software control of Fountain Flow and for cell sorting using Fountain Flow Cytometry. The latter allows for the separation of rare cells from a large volume of water, so that species identification can then be made using other techniques, such as PCR.

The paper that we have written and are about to submit to JAM concerns the use of Fountain Flow Cytometry (FFC) for detection of protozoa and bacteria in raw water with a two-color LED-illuminated FFC system. The system was tested with a flow throughput of 10 ml/minute and amoebae concentrations of 0.06 to 3 amoebae/ml. Two dyes were used, Chemchrome V6, a viability dye, and an R-Phycoerytherin immunolabel. Detections were made in two colors, simultaneously using two cameras and two LED illuminators. Water samples for the Tech River (France) were sampled and tested for background autofluorescence from organic and non-organic material. These experiments show that two-color simultaneous measurements allow us to successfully separate living amoebae at 0.5 to 4 amoebae/ml from background detritus and that we will be able to separate *E. coli* detections from background detritus. Our final experiment in this series, this summer (2010), will be to improve our detections by using RPE-CY7. The draft paper describes our experiments in detail and is attached below as an Appendix (Appendix A).

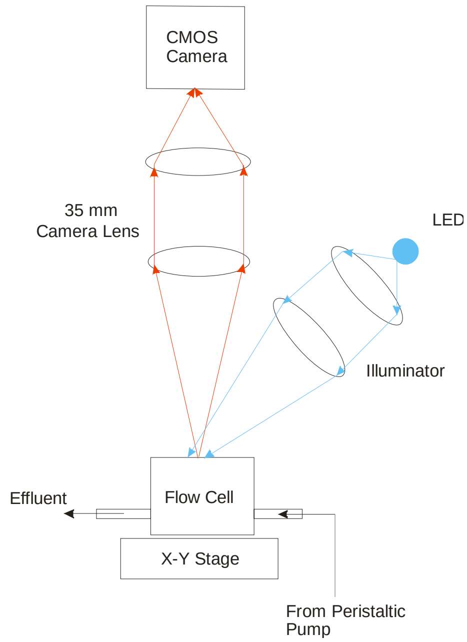
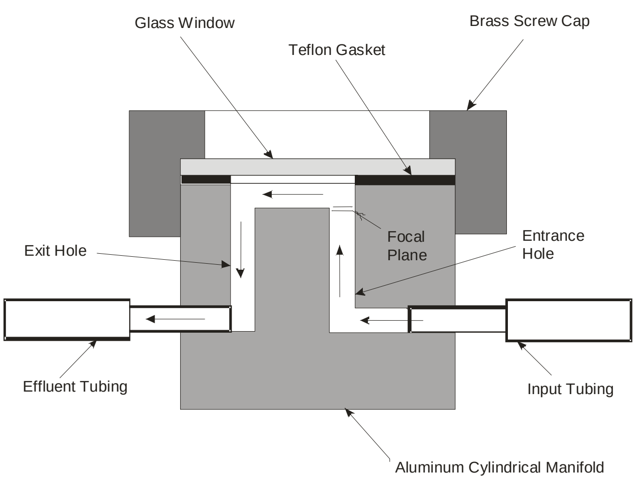


Figure 1. *Schematic diagram of an LED-illuminated epifluorescent Fountain Flow Cytometer. A sample of fluorescently tagged cells flows through the flow cell toward the CMOS camera and fore-optics. The cells are illuminated in the focal plane by an LED. When the cell(s) pass through the CMOS camera focal plane they are imaged by the camera and lens assembly through the transparent flow cell window, and a filter that isolates the wavelength of fluorescence emission. The fluid in which the cells are suspended then passes by the window and out the flow cell drain tube.*



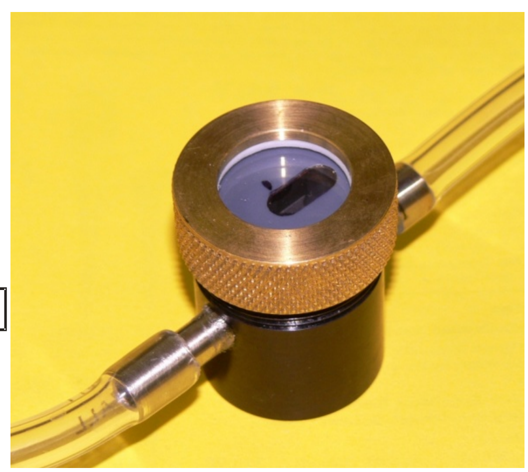


Figure 2. *The Fountain Flow™ Cytometer aluminum flow manifold as used in the device shown in Figure 1 (from Johnson et al., 2006).* ***Upper Panel:*** *The sample enters the flow block through a Tygon tube connected to a stainless steel tube and exits through a stainless steel tube. Two holes have been drilled into the aluminum flow block: an entrance hole and an exit hole. As the sample flows up the internal entrance hole, it passes through the*

focal plane of the CCD/CMOS camera. A Teflon tape gasket is sandwiched between the aluminum flow block and a circular window, and tightly held with a screw-on brass cap. The gasket is cut to form a channel through which the fluid is diverted into the exit hole. ***Lower Panel:*** *A photograph of a working flow block with attached tubing.*

Student Support

During this three-year project, the P-I employed one former undergraduate Pre-Med student, Chris Havens (BS graduate 2006), one geology student, Joseph Johnson (provisional graduate student), and one pharmacy graduate student, Anthony Deromedi in this research. The interaction among personnel of varying backgrounds has provided a highly educational experience for everyone in research biodetection technology.

Publications in Preparation or Submitted from this Project

Manuscripts in Preparation

1. **Johnson, P.E., Havens, C., Lebaron, P., and Catala, P**. *High Throughput, Real-Time Detection of Naegleria lovaniensis in Aqueous Samples using Two-Color Fountain Flow™ Cytometry,* Journal of Applied Microbiology.

Manuscripts Published

1. ***Johnson, P.E., Deromedi, A.J., Lebaron, P., Catala, P., Havens, C., and Pougnard, C.** 2007. *igh throughput, real-time detection of Naegleria lovaniensis in natural river water using LED-illuminated Fountain Flow Cytometry*, **J Appl Microbiol**. **103** (3), 700–710.
2. ***Johnson, P.E., Deromedi, A.J., Lebaron, P., Catala, P., and Cash, J.** (2006) *Rapid detection and enumeration of Escherichia coli in aqueous samples using Fountain Flow™ Cytometry*. **Cytometry Part A**, **69A**, 1212-1221.
3. ***Fini, JB, Pallud-Mothré, Le Mével, S, Palmier, K, Havens, CM, Le Brun, M, Mataix, V, Lemkine, GF, Dememeix, BA, Turque, N, and **Johnson, PE**. (2009) *An innovative continuous flow system for monitoring heavy metal pollution in water using transgenic Xenopus laevis tadpoles*, Environ. Sci. Technol., 2009, 43 (23), pp 8895–8900.

Patents Pending
1. Apparatus and Method for Measuring the Fluorescence of Large Multi-Cellular Organisms, *patent pending*, P.E. Johnson.
2. Method and System for Counting Particles in a Laminar Flow with an Imaging Device, *patent pending*, P.E. Johnson.
3. Method for Pre-Sorting Microorganisms in Aqueous Solution prior to Selective Staining and Detection, *patent pending*, P.E. Johnson.
4. Copyrighted software, including XenopeImage, BioImage, and BioCount, P.E. Johnson.

Patent Granted
1. Apparatus and methods for high throughput analysis of samples in a translucent flowing liquid, P.E. Johnson.

Appendix A:

High Throughput, Real-Time Detection of *Naegleria lovaniensis* in Aqueous Samples using Two-Color Fountain Flow™ Cytometry

INTRODUCTION

This describes study the use of an LED-illuminated Fountain Flow Cytometer™ (FFC) (Johnson et al. 2006, Johnson et al. 2007) to detect amoebae, *Naegleria lovaniensis*, at high flow rates (5 ml/minute) and low concentrations (0.5 to 4 amoebae/ml) in natural river water.

In a previous study (Johnson et al. 2007) FFC was used to measure *N. lovaniensis* incubated with one of two fluorescent labels to facilitate detection: ChemChrome V6, a viability indicator, and an R-Phycoerytherin immunolabel to specifically detect *N. lovaniensis* specifically. The resulting aqueous sample was passed as a stream in front of a light-emitting diode, which excited the fluorescent labels. The fluorescence was detected with a CMOS camera as the sample flowed toward the imager. Detections of *N. lovaniensis* were made in inoculated samples of natural water from eight rivers in France and the US. FFC enumeration yielded results that are consistent with solid-phase cytometry, flow cytometry, and hemocytometry, down to concentrations of 0.06 amoebae/ml, using a flow rate of 15 ml/minute. The result of this study was the detection of *N. lovaniensis*, with a detection efficiency close to 100% within counting statistics. The results of this study indicated that the use of RPE illuminated at 530 nm and detected at 585 nm provides a satisfactory means of attenuating background from natural waters, particularly waters contaminated with chlorophyll-bearing particles. However, under some circumstances the rate of false positive detections was significant when only one color (one excitation wavelength and one emission wavelength) is used. The suggestion was made that using a two-color, simultaneously system would eliminate false positives further: the RPE stain would be selective for *N. lovaniensis* (both live and dead) and avoid background from chlorophyll a and b, while the CV6 stain would label viable cells only and could avoid some false positive detections that were perhaps due to mineral particles or non-chlorophyll fluorochrome.

In the present study we use a two color system to measure emission from RPE and CV6 nearly simultaneously. Two cameras are used to view the flow stream, each with its own LED illuminator/excitation filter and emission filter. The cameras view the flow with the same field of view using a dichroic to divert the green (CV6) image to one camera and the red (RPE) image to a second, identical camera. Images from the two cameras are exposed one after the other as the flow orifice is illuminated first with one LED and then the other. At 5ml/minute the flow rate is slow enough, when using an 8-mm flow cell, so that cells are seen in multiple images and the spatial coincidence for amoebae detected in both cameras is such that the motion in x- and y- between the two colors is less than 50 pixels. At low concentrations, this allows us to be certain, with a high degree of confidence, that we have made a detection of the same target particle in both filters. It also allows us to eliminate dead amoebae, living organisms other than *N. lovaniensis*, and non-organic fluorescent particles from consideration as a detection, thus reducing the rate of false positive detections.

MATERIALS AND METHODS

Amoebae samples. Sample of *Naegleria lovaniensis* were obtained from Pr. Pierre Pernin, School of Pharmacy, University of Lyon. *N. lovaniensis* samples were maintained and cultured in 3ml of SCGYEM liquid medium for three days in the dark at 37° C prior to use as described in De Jonckheere (1977). All measurements were made on *N. lovaniensis* in the trophozoite stage.

Environmental water samples. Environmental samples were take from the Tech River on the 24th of January, 2007 at the Palau del Vidre ford (near Perpignan, France). Samples were refrigerated at about 3° C until use.

Cell staining. ChemChrome V6 (CV6) and R-Phycoerytherin (RPE) were the two fluorescent labels used in this study. ChemChrome V6 is a viability stain which is converted by esterase metabolism in a cell into fluorescein. R-Phycoerytherin is a large-molecule stain. The staining protocol used for CV6 is that described in Johnson *et al*. (2006). Cells were prepared by centrifuging 1 ml of a three-day culture of *N. lovaniensis* at 500-600g for 10 minutes. The resulting pellet was washed and resuspended in 1 ml of 0,2µm filtered Tech water. Then 10 µl of CV6 was added to this sample. (to obtain a “standard” concentration of CV6, although, as we show later, a dose of CV6 20 times smaller was more optimal for our use.) The resulting mixture was incubated at 37 C for 30 minutes in the dark. Small portions, 100 µl, were then removed for flow cytometer enumeration. Afterwards, *N. lovaniensis* were inoculated into natural water samples from the Tech River.   Tech River water was filtered using a 50-µm filter (Buisine).

Cells were stained first with RPE then with CV6. The RPE-immunofluorescent staining was done on live amoebae (for double staining the cells are always alive) samples as described in Johnson et al. (2006), using an antibody specific for *N. lovaniensis* (Indicia Diagnostic, Oullins, France) conjugated with biotin and revealed by streptavidin conjugated with RPE (DAKOCytomation)***.***

First, a relatively high concentration (approximately 1 - 5 × 10^5 amoebae/ml) were stained with RPE in 200 to 500µl of 0.2 micron filtered Tech River water. The result was then diluted in 0.2-micron filtered Tech River water to produce a 2-ml sample. The staining was then confirmed with FCM measurements. Afterward, CV6 staining was performed on the 2ml sample, the sample was diluted into 500-ml of 50-micron filtered Tech River water to the desired final concentration, and FCM measurements were made of the sample. (For FCM measurements, the pre-diluted 2-ml sample is used, or diluted moderately, in order to achieve measurements at concentrations of 1-5 × 10^5 amoebae/ml.) Some FCM measurements were made with 5 replicates for error analysis.

Flow cytometer enumeration of amoebae in Tech River samples. Flow cytometer counts of CV6-labeled *N. lovaniensis* inoculated into Tech River water was performed with a FACSCalibur flow cytometer (FCM) Becton Dickinson) equipped with an air-cooled laser providing 15 mW at 488 nm. Cell discrimination was based on green fluorescence collected in the FL1 channel (530 ± 15 nm). Cells were enumerated during a fixed time (2 to 5 minutes for each sample) at a given flow rate calibrated at the beginning and at the end of each analysis session. Because the low concentrations involved in our FFC sample (0.5 to 4/ml) were under the detection limit for flow cytometry, flow cytometry measurements were made of a relatively concentrated sample of a staining of cells (1-5 × 10^5 amoebae/ml). Five 1-ml sub-samples of this suspension were analyzed by FCM to give an mean concentration and standard error of the mean. Finally the last dilution was made in 500ml of 50-micron filtered Tech River water to give the desired concentration (0.5, 1.0, 2.0, or 4.0 amoebae/ml) for FFC, measurements.

FFC enumeration of Tech River samples. FFC enumeration. Samples were placed in a glass bottle with a magnetic stir bar and introduced into the FFC with a peristaltic pump (Reglo). The magnetic stirrer prevented sedimentation of amoebae in the sample during the sampling process. For each sample enumerated with the FFC, the sample was counted in multiples of 100 frames (each RPE frame consisting of a 400 ms exposure and each CV6 frame a 100 ms exposure with 50 ms between the two); each set of 100 frames representing a sub-sample. A mean and standard deviation was produced from the ensemble of the 100-frame sub-samples representing a single sample.

Peristaltic pump rates for the two peristaltic pumps used in our experiments were continuously calibrated during the sampling period by weighing the FFC effluent on a digital scale. Variations in pump rate between such calibrations were within approximately 5%. Although the nominal pump rate throughout this study is 5 ml/minute, all data were adjusted to the measured pump rate. All FFC data were taken with SEMRock filters designated for RPE (CY3-4040B filter set, with an excitation filter at 531 nm, 40 nm bandwidth and an emission filter at 593 nm and 40 nm bandwidth) and FITC (FITC-3540B filter set with an excitation filter at 482 nm, 35 nm bandwidth and an emission filter at 536 nm, and a 40 nm bandwidth).

RESULTS

FFC measurements of filtered Tech River water to determine the rate of false positive detections from detritus. Although no measurements were made of uninoculated river water in this study we have made measurements of fixed amoebae inoculated into 50-micron filtered Tech River water samples. Measurements of four 15-ml samples of Tech River water with 4.0/ml fixed amoebae were made. The amoebae, double-stained with CV6 and RPE, as above, were detected in the RPE channel, although at a level where not all dead amoebae were counted (Figure 5). No detections were made in the CV6 channel, so neither Figure 6 (CV6 channel) nor Figure 7 (combined channels) shows detections. In summary, these five samples showed no false detections in the two combined channels from natural, 50-micron filtered river water filtered inoculated with fixed amoebae.

Measurements of single stained CV6- and RPE-labeled amoebae in buffer. Figure 5 shows a plot of FFC counts vs. FCM counts for 15-ml samples of inoculated Tech River samples of RPE-labeled amoebae, spanning the range of 0.5 to 4 amoebae/ml, at a sampling rate of approximately 5 ml/minute. The best-fit line to the data has a slope of 1.88 ± 0.13 (95% confidence limit) and an intercept of 17.8± 5.9. The R^2 of the fit is 0.92. The slope of the fit indicates a higher count rate with FFC than with flow cytometry. The fact that the slope is significantly greater than 1.0 is due to a high rate of false positive counts from FFC.

Figure 6 shows a plot of FFC counts vs. FCM counts for 15-ml samples of inoculated Tech River samples of CV6-labeled amoebae, spanning the range of 0.5 to 4 amoebae/ml, at a sampling rate of approximately 5 ml/minute. The best-fit line to the data has a slope of 1.65 ± 0.14 (95% confidence limit) and an intercept of 11.2 ± 6.2. The R^2 of the fit is 0.90. The slope of the fit again indicates a high rate of false positive detections from FFC.

Measurements of double stained CV6- and RPE-labeled amoebae in buffer. Figure 7 shows a plot of FFC counts vs. FCM counts for 15-ml samples of inoculated Tech River samples of amoebae labeled with both CV6 and RPE, spanning the range of 0.5 to 4 amoebae/ml, at a sampling rate of approximately 5 ml/minute. The best-fit line to the data has a slope of 0.96 ± 0.04 (95% confidence limit) and an intercept of -2.0 ± 2.1. The R^2 of the fit is 0.96. The slope of the fit is insignificantly different from 1.0 and the intercept insignificantly different from 0.0, indicating near perfect agreement between FFC and FCM enumeration.

Note: Subsequent attempts to repeat our measurements indicate that we have two problems: lack of signal intensity combined with emission of CV6 into the red (RPE) channel. Measurements of cells stained with

CV6 only were detected in the red channel. We are currently rectifying this problem and have produced (as of 2010) a Fountain Flow system that has ~20-50x the signal-to-noise of the system that we used in 2008, and using CV6 with a dye that emits in the redder part of the spectrum (RPE-CY5 or RPE CY7). We no longer believe that the data included here are truly representative of the concentrations of viable and non-viable *N. lovaniensis.*

ACKNOWLEDGEMENTS

The authors acknowledge funding from C.N.R.S., Electricité de France, the US Geological Survey, and the Wyoming Water Development Commission in support of this project.

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Figures

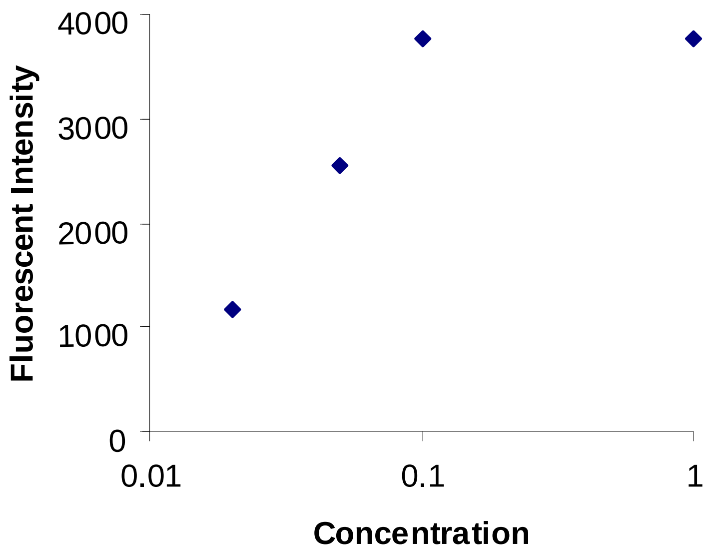

Figure 1. *Fluorescent intensity vs. concentration of CV6 in solution, relative to recommended level of CV6. We used 1/20th the normal concentration which gave good signal to noise in the CV6 channel, and minimal emission in the RPE channel.*

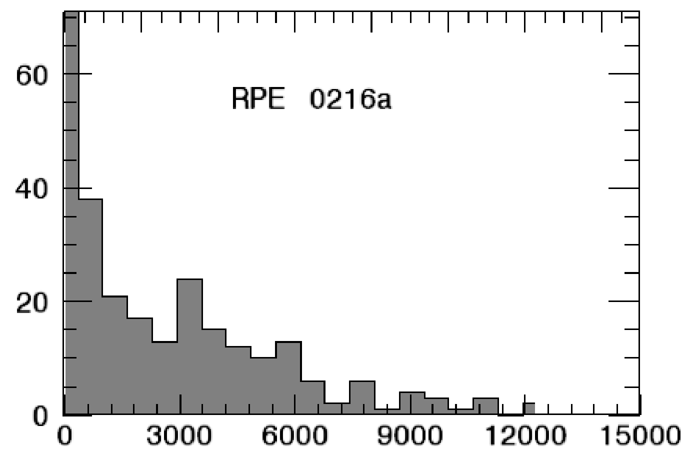

Figure 2. *Histogram of intensities (in ADUs) using the red channel to identify viable amoebae. Histogram of one sample of live N. lovaniensis intensity in Tech River water with 4.0 amoebae/ml. Amoebae are stained with RPE labeled antibody and CV6. The intensities shown here are for the RPE (red) channel. Notice the significant abundance of low-intensity particles.*

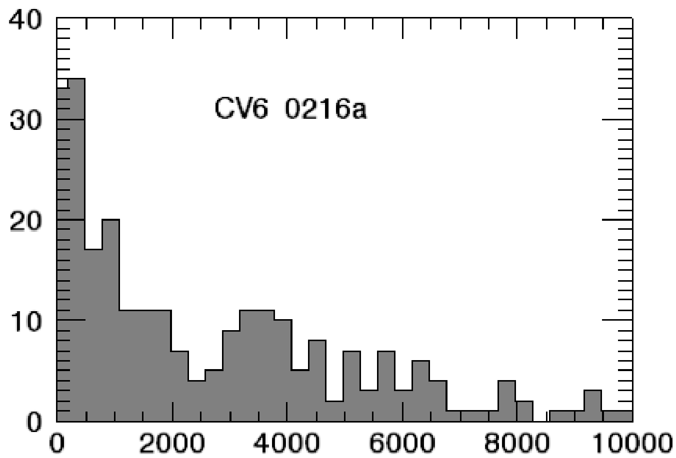

Figure 3. *Histogram of intensities (in ADUs) using the green channel to identify viable amoebae. This histogram represents one sample of live N. lovaniensis intensity in Tech River water with 4.0 amoebae/ml. Amoebae are stained with RPE labeled antibody and CV6. The intensities shown here are for the CV6 (green) channel. Notice the significant abundance of low-intensity particles.*

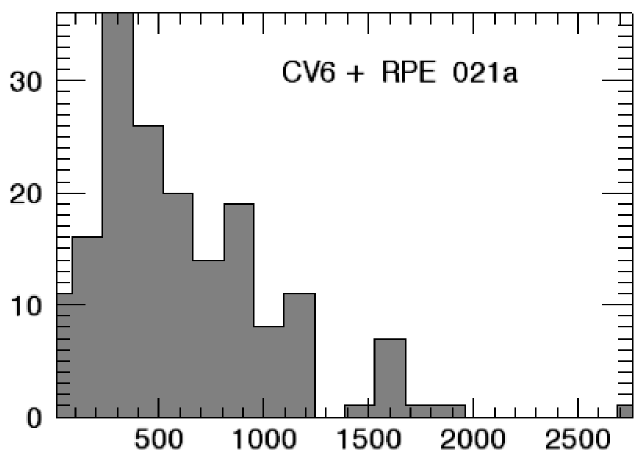

Figure 4. *Histogram using both channels to define viable amoebae. This histogram represents one sample of live N. lovaniensis intensity in Tech River water with 4.0 amoebae/ml. Amoebae are stained with RPE labeled antibody and CV6. The intensities shown here are for the RPE (red) channel. Notice the distinct peak at 500 ADUs and the lack of a significant abundance of low-intensity particles compared to Figures 2 and 3. All particles with more than 1000 ADUs in the green channel AND 200 ADUs in the blue channel are shown. In other words in this Figure the selection is based on both channels*

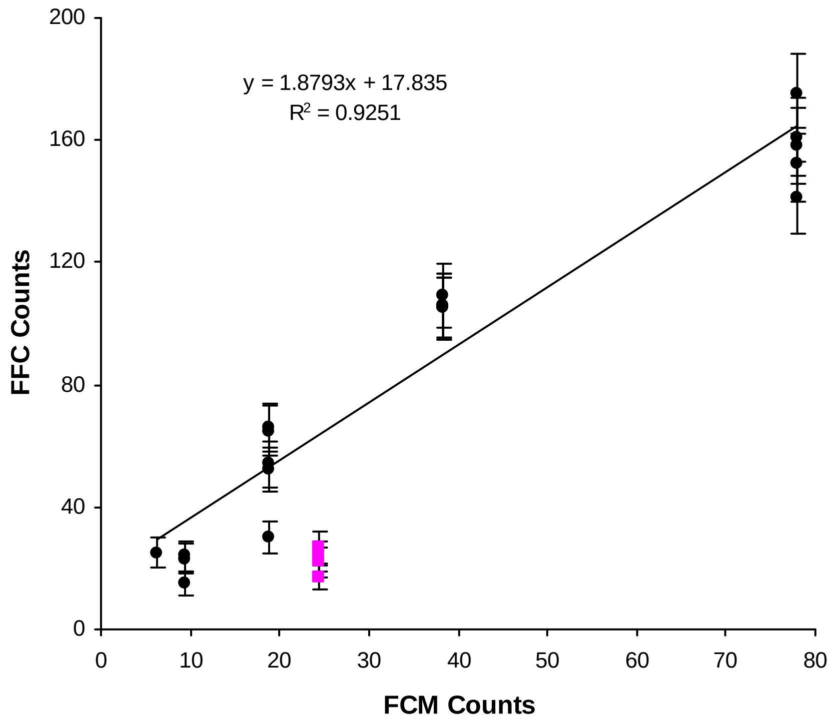

Figure 5. *Comparison of FFC and FCM counts determined by red channel intensity. FFC and FCM counts (number of amoebae/ml) are given for 15ml samples, made by counting all particles with more than 200 counts in the red (RPE) channel in samples stained with RPE in Tech River water filtered only with a 50-µm filter. Live amoeba samples are shown as dark blue diamonds, dead (fixed) amoebae samples with violet squares. The large slope of the line is due to the counting of particles that are not amoebae*.

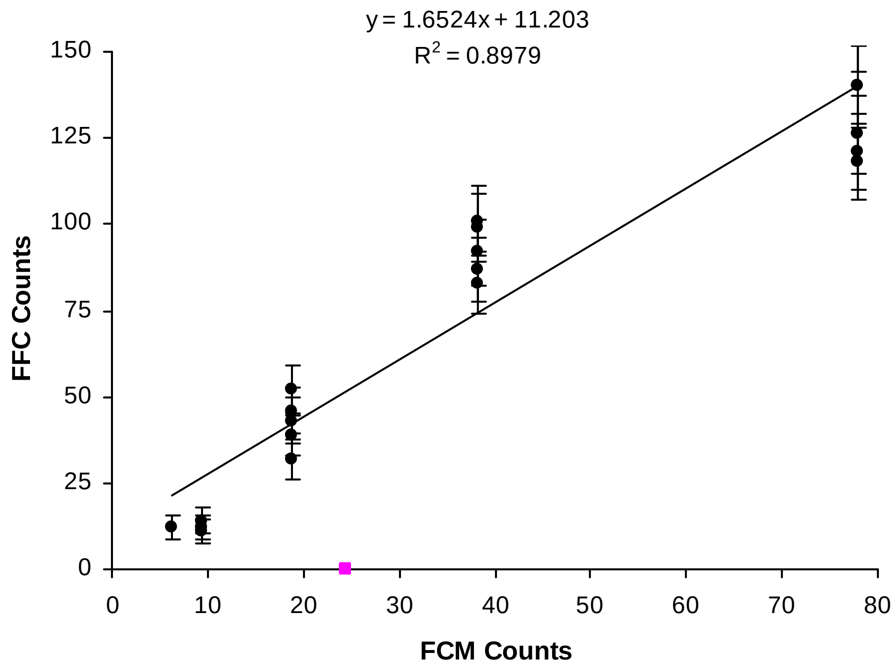

Figure 6. *Comparison of FFC and FCM counts determined by green channel intensity only. FFC and FCM counts (number of amoebae/ml) are given for 15ml samples, made by counting all particles with more than 1000 counts in the green (CV6) channel in samples stained with both RPE and CV6 in Tech River water filtered only with a 50-µm filter. Live amoeba samples are shown as dark blue diamonds, dead (fixed) amoebae samples with violet squares. The large slope of the line is due to the counting of particles that are not amoebae*.

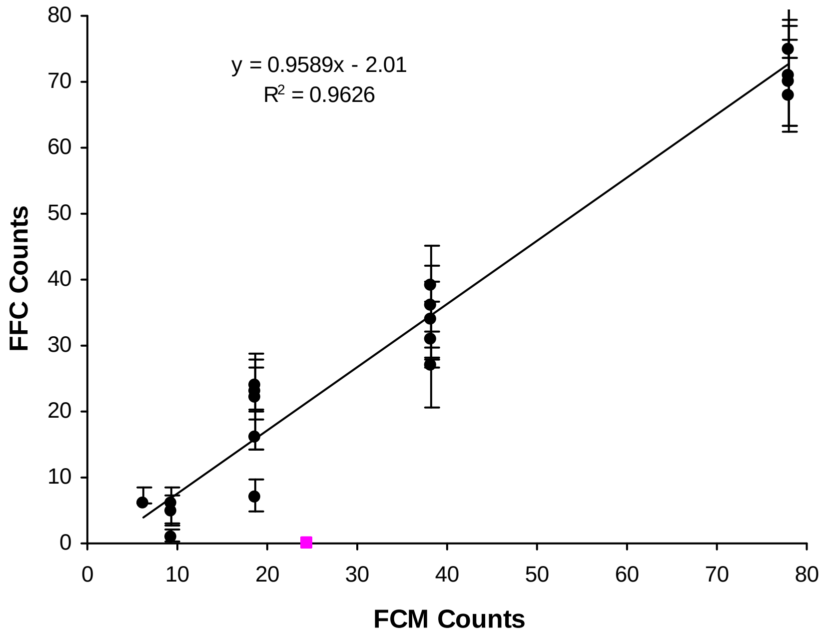

Figure 7. *Comparison of FFC and FCM counts determined by both green and red channel intensities. FFC and FCM counts (number of amoebae/ml) are given for 15ml samples, made by counting all particles with more than 1000 counts in the green (CV6) channel and 200 counts in the red (RPE) channel in samples stained with both RPE and CV6 in Tech River water filtered only with a 50-µm filter. Live amoeba samples are shown as dark blue diamonds, dead (fixed) amoebae samples with violet squares. Note: The data used in Figures 5, 6, and 7 are from the same data set, but only the criteria for a detection was changes. Also note that the R^2 is much higher for this Figure than Figures 5 and 6.*

Integrated Management of Groundwater and Surface Water Resources: Investigation of Different Management Strategies and Testing in a Modeling Framework

Basic Information

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Integrated Management of Groundwater and Surface Water Resources: Investigation of Different Management Strategies and Testing in a Modeling Framework

Final Report

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Executive Summary

The application of non-conjunctive prior-appropriation allocation strategies to groundwater resources has the potential to curtail water surface water availability. Predictive understanding of the interactions of groundwater wells with surface water rights for management purposes requires a model to ascertain the worth of different management strategies. The degree of impact of a management scheme for groundwater pumping will depend on aquifer properties, degree of connectedness between surface water and groundwater, pumping history and rates, recharge, projected demands on use, and the particular management strategy employed.

Methods: We performed a detailed investigation of groundwater-surface water management strategies used in Western states, and examined the implications of different management strategies on the water rights of surface and ground water water rights holders. A policy study was conducted in a legal framework that considered the application of different policies in other states as they relate specifically to Wyoming law. The *MODFLOW*-based Groundwater Management model (*GWM*), which simulates the effect of different groundwater pumping configurations on surface water depletions was set up an on the Bates Creek Irrigation District near Casper, Wyoming, an example modeling framework that can be used to to determine the impact of the different management strategies on surface and groundwater rights in a stream underlain by an alluvial aquifer.

Objectives: The objectives of this research project were to:

1) produce a complete list of existing viable potential strategies for conjunctive management of surface and groundwater rights in alluvial aquifers;
2) study of the effect of variables such as surface water flow rate, streambed conductivity, groundwater pumping rate per unit area, aquifer properties, distance of wells from stream, on the impact of each management strategy on the rights of surface and groundwater permitees; and,
3) transfer results to the State Engineer's office, and assist in interpreting policy and setting up the model in specific locations of interest to the State Engineer’s Office.

Deliverables: Policy details and legal analysis pertaining to the management of conjunctive surface and ground waters within the prior-appropriation water rights doctrine. A contemporary modeling framework that can be used by the Wyoming Office of State Engineer to test conjunctive management strategies in specific areas of interest.

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APPENDIX A 73

1. Legal Analysis of Ground Water and Surface Water Conjunctive Management Within the Context of Wyoming Water Law

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Introduction

This report summarizes a detailed investigation of groundwater-surface water management strategies (referred to here as "conjunctive management" used in several Western states. The research was based on the hypothesis that the application of allocation strategies to groundwater resources has the potential to curtail water groundwater availability and that the potential interactions with surface water rights requires a model to ascertain the value of different management strategies. The degree of impact of a management scheme for groundwater pumping depends on aquifer properties, degree of connectedness between surface water and groundwater, pumping history and rates, recharge, projected demands on use, and the particular management strategy employed.

This research comes at an important time in the development of conjunctive management strategies. Recently, both Wyoming and Idaho's conjunctive management approaches survived legal challenges. In both cases, however, questions remain regarding the implementation of those management strategies. In Idaho, the Supreme Court ruled that the state's conjunctive management regulations were "facially valid" under Idaho's prior appropriation doctrine but did not have an opportunity to rule on whether the State Engineer's application of the law as applied to a specific set of management decisions would survive scrutiny (*American Falls Reservoir District v. IDWR*, 2007). Similarly, a Wyoming district court recently upheld the State Engineer's decision to restrict groundwater users to meet surface use demands under the state's conjunctive management approach, but, for procedural reasons there was no appeal, and future legal challenges are likely (*Rivett v. Wyoming State Engineer's Office*, 2009).

In states where both the ground and surface waters are managed using a prior appropriation approach, conjunctive management may be necessary in order to protect senior appropriators with permits from both hydrological systems. The challenge becomes how to manage ground and surface waters conjunctively when there is limited hydrologic data regarding interconnectivity, forecasting of surface flows and groundwater recharge rates.

Methods

On the policy front, the research into relevant conjunctive management strategies was three-fold: (1) traditional legal research into the ground and surface water management strategies of Wyoming, Idaho, Colorado, Washington and Arizona; (2) primary interviews with state agency officials and other important individuals within the different jurisdictions; and (3) peer review of findings with key water experts in the field.

An investigation of the legal approaches of the selected states was conducted using relevant, statutes, regulations and case law. In addition, newspaper articles, peer-reviewed and gray literature was used, as appropriate, in order to assess the current state of conjunctive management in each state and identify examples of conjunctive management approaches and outcomes.

In addition, we conducted a series of semi-structured interviews of water experts in the selected states. Interviewees were assured anonymity and asked several questions designed to elicit their opinions of both the research findings conducted during the legal research phase of the project and their views of how management was occurring in their states (see Appendix "A"). Questions asked of the experts included:

> (1) What has been your experience with your state's attempt to conjunctively manage ground and surface water resources and/or address conflict between surface and ground water users? Would you describe the experience as positive, negative? Why or why not?
>
> (2) Do you have any suggestions for how your state could improve its management of ground and surface water use conflicts?
>
> (3) Can you provide any examples of specific ground and surface water interactions in your state that inform your answers to questions 1 and 2?
>
> (4) What, in your opinion, is the greatest barrier to effective conjunctive management in your state?
>
> (5) Do you feel like your state has the necessary technical/hydrologic information necessary to implement its management scheme? Why or why not? What would improve the situation?

The results of these interviews are included in the individual state summaries and are also summarized in the results and discussion section.

Wyoming

Wyoming Overview

According to Wyoming's Constitution, priority of appropriation for beneficial water uses is the guiding doctrine in Wyoming and it is to be administered by the Board of Control (Wyoming Constitution, Article 8 §§ 1-3). Any person seeking to appropriate groundwater must seek a permit from the State Engineer (Wyoming Statute § 41-3-930(a)). If the State Engineer determines that the surface and groundwater in a particular area constitutes "one source of supply," then both shall be administered under a single set of priorities (Wyoming Statute § 41-3-916). In order to administer groundwater supplies, the Board of Control may designate "control areas" if:

1) groundwater use exceeds, equals or is approaching the recharge rate;
2) conflicts between users are ongoing or foreseeable;
3) waste of water is or may be occurring; or
4) other conditions exist that require such designation (Wyoming Statute § 41-3-912).

Once a "control area" is established, the State Engineer is then authorized to adopt corrective controls (Wyoming Statute § 41-3-915). Such corrective controls that the State Engineer may institute include:

1) closing the control area to any new appropriations or instituting well-spacing regulations for new appropriations;
2) ordering junior groundwater users to cease withdrawals; or
3) determining the total withdrawal for a particular day, month or year and apportioning such withdrawal in respect to priority dates (Wyoming Statute § 41-3-915).

Wyoming Constitutional Provisions

Wyoming's State Constitution contains provisions relating to the management and distribution of water. As such, all legislative and agency statutes and regulations must conform to the guidelines set forth in the Wyoming Constitution. Article 8 Section 1 of the Wyoming Constitution declares that "[T]he water of all natural streams, springs and lakes…are property of the state" (Wyoming Constitution, Article 8 § 1). In other words, "water is the property of the state, under control by the state and held in trust for its people" (*Hunziker v. Knowlton*, 1958).

Article 8 Section 3 adopts the prior appropriation doctrine by stating: "[P]riority of appropriation for beneficial uses shall give the better right. No appropriations shall be denied except when such denial is demanded by the public's interest" (Wyoming Constitution, Article 8 § 3). Appropriable water is that water "which if not intercepted would naturally reach a stream" (*Bower v. Big Horn Cana*l, 1957). Percolating waters developed by excavations or other artificial means do not belong to the state, rather they belong to the owner of the land upon which they are developed.

Article 8 Section 2 establishes that "[T]here shall be a board of control, composed of the state engineer and superintendents of water divisions…which under such regulations have the supervision of the waters of the state and their appropriation, distribution and diversion" (Wyoming Constitution, Article 8 § 2).

Overall, the Wyoming State Constitution establishes:

1) any water, except such water that is defined to be percolating water, is property of the state held in trust for the people of the state;
2) priority of appropriation is the guiding doctrine of Wyoming water law;
3) water subject to appropriation is any water which would naturally reach a stream;
4) only beneficial uses of water may give rise to an appropriation;
5) an appropriation of water typically may not be denied if there is available water to appropriate; and
6) the Board of Control is responsible for regulating the appropriation, distribution and diversion of Wyoming's waters.

Wyoming Groundwater Management

Groundwater is defined as "any water, including hot water and geothermal steam, under the surface of the land or the bed of any stream, lake, reservoir, or other body of surface water, including water that has been exposed to the surface by an excavation" (Wyoming Statute § 41-3-901(a)(ii)). "Rights to underground water shall be subject to the same preferences as provided by law for surface users" (Wyoming Statute § 41-3-906). Therefore, underground water is appropriated similar to surface water and is also subject to beneficial use requirements.

Pursuant to Wyoming Statute § 41-3-905, "[N]o well shall be constructed…unless a permit has been obtained from the state engineer" (Wyoming Statute § 41-3-930(a)). Thus, any person seeking an appropriation of groundwater must file a groundwater application with the state engineer (Wyoming Statute § 41-3-905). Permits will typically be granted as a matter of course, unless the proposed well lies within a groundwater control area (Jacobs et al., 2003, p. 6).

"It is an express condition of each groundwater permit that the right of the appropriator does not include the right to have the water level or artesian pressure…maintained at any level or pressure higher than that required for maximum beneficial use of the water in the source of supply" (Wolfe et al., 1989). Since maximum beneficial use is a permit requirement, the appropriator is responsible for maintaining a well at an adequate depth with a sufficient pump.

A 'control area' is "any underground water district or sub-district that has been so designated by the Board of Control" (Wyoming Statute § 41-3-912). A control area may be designated where:

i. the use of underground water is approaching a use equal to the current recharge rate;
ii. groundwater levels are declining or have declined excessively;
iii. conflicts between users are occurring or are foreseeable;
iv. the waste of water is occurring or may occur; or
v. other conditions exist or may arise that require regulation for the protection of the public interest. (Wyoming Statute § 41-3-912)

Future groundwater permits in control areas are only granted if the state engineer finds that "there are inappropriate waters in the proposed source, that the proposed means of diversion or construction is adequate, that the location of the proposed well does not conflict with any well spacing or well distribution regulation, and that the proposed use would not be detrimental to the public interest" (Wyoming Statute § 41-3-932(c)).

The State Engineer is authorized to adopt corrective controls in control areas where it appears immediate regulation is necessary (Wyoming Statute § 41-3-915). In fact, the state engineer must hold a hearing on the necessity for and utilization of corrective controls if twenty appropriators or one-tenth of the appropriators in a control area petition for a hearing (Wyoming Statute § 41-3-915). After such hearing, the state engineer may adopt corrective controls (Wyoming Statute § 41-3-915). Corrective controls that the state engineer may order include:

i. closing the controlled area to any further appropriation of underground water;
ii. determining the permissible total withdrawal of underground water in the control area for each day, month or year and apportioning such total in accordance with the relative dates of priority of such rights;
iii. ordering junior appropriators to cease or reduce withdrawals;
iv. ordering a system of rotation of use of underground water if he finds that cessation or reduction by juniors will not result in proportionate benefits to senior appropriators; or
v. instituting well spacing requirements if permits are granted for new wells. (Wyoming Statute § 41-3-915)

"Appropriations of underground for stock or domestic use…shall have preferred right over rights of all other uses, regardless of their dates of priority" (Wyoming Statute § 41-3-907). A domestic use is defined as "household use including lawn and garden watering for non-commercial family use where the area to be irrigated does not exceed 1 acre" (Wyoming Statute § 41-3-907). The maximum quantity of water that can be pumped and qualify for the domestic use exception is 25 GPM (Wyoming Statute § 41-3-907).

Groundwater subject to appropriation is defined under Wyoming Statute § 41-3-901(a)(ii). A permit from the State Engineer is necessary for a groundwater appropriation. Groundwater permits will typically be granted unless the area where such permit is sought lies in a control area. (Figure 1) Control areas are designated by the Board of Control, when the Board of Control determines that conditions, delineated under Wyoming Statute § 41-3-912, exist. The state engineer must determine that there is unappropriated groundwater to issue new permits in control areas. The state engineer may adopt corrective controls in control areas. These corrective controls may include shutting off the wells of junior appropriators.

Wyoming: Conflict Between Surface and Groundwater Users

Wyoming Statute § 41-3-916 states, "[W]here underground waters in different aquifers are so interconnected as to constitute in fact one source of supply, or where underground waters and the waters of surface streams are so interconnected as to constitute in fact one source of supply, priorities of rights to the use of all such interconnected waters shall be correlated and such single schedule of priorities shall relate to the whole common water supply" (Wyoming Statute § 41-3-916). In fact, every groundwater permit includes an express condition that it may be subject to correlation with surface water rights if the ground and surface water are determined to be interconnected. Therefore, once the State Engineer determines that the underground and surface waters constitute "one source of supply," priority dates for both adhere to a single set of priorities. Thus, a common theme in Wyoming's water conflicts has been one of proving connectivity between ground and surface water sources and its effect on the enforcement of priority rights.

Figure 1: National Park Service.Teton Reflection in Beaver Pond. Retrieved July 16, 2009, from http://national-park.of-the-week.com/grand_teton.html

Wyoming Outcomes and Challenges: Rivett v. Wyoming State Engineer's Office

As has been true for each of the states examined in this study, Wyoming has experienced conflicts with management of surface and groundwater. The case in interest here was instigated in 2007 in Natrona County in central Wyoming and centered on the need burden of proving connectivity between surface and groundwater sources before priority curtailments can be ordered.

In spring of 2007 Mr. Charles Scott of the Bates Creek Cattle Company, a surface water user with a priority right dating to 1886, made a request for regulation to the local water Commissioner. The Commissioner subsequently ordered the shutdown for the rest of the summer of some wells that were located upstream of the Cattle Company's diversion from Bates Creek and junior in priority right. These included three wells owned by Dennis and Sherry Rivett, which they used for irrigation. The priority dates for the Rivetts' groundwater wells are 1976 and 1977.

The Rivetts appealed the curtailment order to the Superintendent of their water district. The Superintendent denied the appeal and the Rivetts appealed that decision to the State Engineer. The State Engineer sided with the Commissioner and the Superintendent to again deny the appeal, after which the Rivetts took the case to the 7th District Court in Wyoming by submitting a petition for review of the State Engineer's decision. The case rested in the court through the winter of 2007-08 with both the petitioners and the respondent, the State Engineer, submitting briefs.

Figure 2: Photo by Yingling, Rob (BighornMountains.com, LLC). Wind River Canyon. Retrieved June 30, 2009, http://www.bighornmountains.com/photo-gallery/thermopolis.htm

In spring of 2008 Mr. Sherman Drake, a surface water user with a right in the Bowie #1 Ditch dating to 1886, made a request for regulation to the water Commissioner similar to the request made by the Bates Creek Cattle Company the previous summer. Bowie #1 Ditch contains surface water diverted from Bates Creek at a headgate downstream from the Rivetts' and wells. Again, the Commissioner subsequently ordered the shutdown for the rest of the summer of several upstream wells including the same three Rivett wells and two wells owned by David and Jenise Whisler. The Whisler wells are used for irrigation and have priority dates of 1971. As had happened the previous year, both the Rivetts and the Whislers appealed to the water Superintendent, then to the State Engineer, and finally to the 7th District Court as each appeal was denied along the way.

The groundwater users claim that the orders to shut down their wells were unlawful and ask the District Court to reverse that order. The main arguments: 1) the State Engineer did not have substantial evidence to prove that withdrawals of groundwater from their wells was affecting the surface water users who issued the requests to have them regulated, and 2) the well owners were not given due notice or a chance to defend their water rights in a hearing before they were ordered to shut down.

In November 2008 the three cases—the Rivett case from 2007 and the Rivett and Whisler cases from 2008—were consolidated and assigned to a new judge in the district court as the original judge hadn't found time to work on the cases. A hearing was held in District Court for April 3, 2009, soon after which the court ruled in favor of the State Engineer's Office and upheld their management action.

During an oral ruling on April 22, 2009 that was later incorporated into a court order, the court stated: "the only evidence in the record establishes that when petitioners turn on their ground water wells, it has a direct, ultimately, impact on the surface water levels of Bates Creek. Given such evidence, this Court cannot conclude that the findings were inadequate." Due to a procedural error, appeal to the Wyoming Supreme Court was denied. As a result, it is likely that similar claims may be raised again in future litigation.

Figure 3: U.S. Geological Survey, North Platte River in Wyoming. Retrieved 26 April 2010, from http://wy.water.usgs.gov/projects/drought/images/

Wyoming Outcomes and Challenges for the Future

According to Wyoming state law, "where underground waters and the waters of surface streams are so interconnected as to constitute in fact one source of supply, priorities of rights to the use of all such interconnected waters shall be correlated and such single schedule of priorities shall relate to the whole common water supply. The state engineer may by order adopt any of the corrective controls specified in [the Wyoming statutes]."

On major challenge centers on who bears the burden of proofing the connectivity of ground and surface waters. "Whose responsibility is it to prove connectivity? In our study we said the water sources are connected," says one person interviewed at the SEO. "The groundwater users never proved they were not connected. They had that opportunity to refute our findings and they never did. On the back of our water rights it says that the water application is approved subject to the condition that the proposed use will not interfere with other water rights. Every water right carries a risk in that if it interferes with other existing water rights it can be revoked. People never realize that until it's too late. They get upset because their wells get shut down for two weeks and all the crops for the year die, but from the beginning each water right holder runs the risk of having their water curtailed. We're pretty clear with that up front that water right is at risk. We're trying to find a better management solution right now."

Idaho

Idaho Overview

Idaho's State Constitution specifically adopts the doctrine of prior appropriation. The Idaho Department of Water Resources (IDWR) is responsible for administering and developing regulations for the state's prior appropriation system (Raines, 1996). Any person seeking to appropriate groundwater must get a permit from IDWR (Raines, 1996) (Figure 4).

Figure 4: Photo by Carlson, Dave. South Fork of the Snake River above Heise, Idaho. Retrieved July 15, 2009, from http://www.idwr.idaho.gov/waterboard/WaterPlanning/CompBasinPlanning.htm

Idaho has adopted a comprehensive set of rules for the conjunctive management of surface and groundwater for "areas determined to have a common groundwater supply" (Idaho Administrative Procedure Act, Section 37). For these areas, the director of IDWR has the duty to respond to delivery calls made by senior surface or groundwater users against junior groundwater pumpers (Idaho Administrative Procedure Act, Section 37). The Conjunctive Management Rules apply when the senior water user is found to suffer material injury due to the pumping of junior groundwater users. The most important factor in determining whether there is material injury is whether the junior groundwater rights affect the quantity and timing of water available to a senior user or the cost of exercising the senior water right (Idaho Administrative Procedure Act, Section 37). However, the senior's available storage water and the extent to which the senior's water right could be met by employing alternative reasonable diversion means and conservation practices are factors to be considered in determining material injury. If material injury is found, the junior's pumping will be curtailed unless the junior has an approved mitigation plan (Idaho Administrative Procedure Act, Section 37). A mitigation plan "identifies actions and measures to prevent, or compensate holders of senior-priority water rights for, material injury caused by the diversion and use of water by the holders of junior-priority groundwater rights" (Idaho Administrative Procedure Act, Section 38.03.11.000.15).

Idaho Constitutional Provisions

Article XV of the Idaho Constitution is dedicated entirely to water rights. According to Article XV § 3, the use of water is declared a public right and "the right to divert and appropriate the unappropriated waters of any natural stream to beneficial uses shall not be denied." Furthermore the appropriation doctrine is the guiding principle as "[P]riority of appropriation shall give the better right as between those using the water" (Idaho Constitution, Article XV, § 3).

Idaho Groundwater Management

IDWR is responsible for administering and developing rules and regulations for both surface and groundwater under the state's prior appropriation system (Raines, 1996). The director of IDWR supervises water distribution within each district, while the district water masters distribute water according to priority and shut off headgates in times of scarcity (Idaho Code § 42-604).

Idaho requires permits to appropriate groundwater (Idaho Code § 42-202). Any person seeking a permit to pump groundwater must apply to IDWR before commencing construction. Wells used for domestic purposes do not require a permit provided that the drilling is authorized by a license and subject to inspection by IDWR and the Idaho Department of Environmental Quality (IDEQ) (Idaho Code § 42-202).

Conjunctive management rules apply to "areas determined to have a common groundwater supply" (Idaho Administrative Procedures Act, Section 37). The "rules apply to all situations where the diversion and use of water under junior-priority groundwater rights either individually or collectively causes material injury to uses of water under senior-priority water rights … The rules acknowledge all elements of the prior appropriation doctrine as established by Idaho law" (Idaho Administrative Procedures Act, Section 37).

The conjunctive management rules describe IDWR's procedures for responding to a water delivery call made by a senior surface or groundwater user against a junior groundwater user (Kray, 1996). In order to initiate a delivery call, a senior water user must file a petition that includes: a description of the senior's water right, names and addresses of the groundwater users who are alleged to cause material injury and any data or information to support the claim of material injury (Idaho Administrative Procedures Act, Section 37). If material injury is found, the director must "regulate the diversion and use of water in accordance with the priorities of rights of the various surface or groundwater users," but the director may lessen the economic impact by declining immediate and complete curtailment if the material injury is long range or delayed (Idaho Administrative Procedures Act, Section 37)(figure 2).

Rule 42 lists factors that the director may consider in determining whether the senior has suffered material injury and whether the senior is utilizing his water right without waste (Idaho Administrative Procedures Act, Section 37). Of importance is "[W]hether the exercise of junior-priority groundwater rights individually or collectively affects the quantity and timing of when water is available to, and the cost of exercising, a senior-priority surface or groundwater right" (Idaho Administrative Procedures Act, Section 37). However, among the factors to be considered are the extent to which the senior's water right could be met by employing reasonable diversion and conveyance efficiency and conservation practices and the extent to which the senior's water right could be met using an alternate reasonable means of diversion, including the construction of wells (Idaho Administrative Procedures Act, Section 37). Factor (g) of conjunctive management Rule 42.01 allows the director to consider the senior's available storage water in determining whether the senior has suffered material injury (Idaho Administrative Procedures Act, Section 37).

Figure 5: Photo by High, Jac, (Go Northwest, Inc.). Shoshone Falls on Snake River, Twin Falls, ID. Retreived April 26, 2010 from: http://www.gonorthwest.com/Idaho/southcentral/idsc.htm.

Rule 40 permits junior-priority users to maintain their groundwater pumping if they have an approved mitigation plan (Idaho Administrative Procedures Act, Section 37). A mitigation is "[A] document submitted by the holder(s) of a junior-priority groundwater right and approved by the director as provided in Rule 043 that identifies actions and measures to prevent, or compensate holders of senior-priority water rights for, material injury caused by the diversion and use of water by the holders of junior-priority groundwater rights within an area having a common groundwater supply" (Idaho Administrative Procedures Act, Section 37). Rule 43 lists the procedures to be followed and the factors to be considered in approving a junior's mitigation plan. Of importance is "whether the mitigation plan will provide replacement water, at the time and place required by the senior-priority water right, sufficient to offset the depletive effect of groundwater withdrawal on the water available in the surface or groundwater source at such time and place as necessary to satisfy the rights of diversion from the surface or groundwater source” (Idaho Administrative Procedures Act, Section 37). However, “consideration will be given to the history and seasonal availability of water for diversion so as not to require replacement water at times when the surface water right historically has not received a full supply, such as during annual low-flow periods and extended drought periods” (Idaho Administrative Procedures Act, Section 37).

Idaho: Conflict between Surface and Groundwater Users

Until 1994, IDWR issued permits for groundwater pumping, regardless of the effects upon surface users (Idaho Code § 42-202). However, the Idaho Supreme Court case of *Musser v. Higginson* caused IDWR to change its groundwater management rules and policies. In Musser, the court held that the failure to deliver water, due to interfering groundwater pumping, to the senior surface user was arbitrary and capricious under Idaho Code § 42-602 (*Musser v. Higginson*, 1994). Following Musser, IDWR adopted the most comprehensive set of conjunctive management rules of any state. These rules were subsequently found to be facially constitutional in the Idaho Supreme Court case *American Falls Reservoir District v. Idaho Department of Water Resources* (March 2007).

In *American Falls*, the Idaho Supreme Court clarified that the director should have some discretion to determine whether the carryover water is reasonably necessary for future needs. The court reasoned that “first in time” is subject to beneficial use and to permit excessive carryover water would be in itself unconstitutional (*American Falls Reservoir District v. IDWR*, 2007).

Idaho: Outcomes and Challenges

In the winter of 2005, Idaho water users steeled themselves for what would be the 6th year of a drought that had diminished water throughout the West. The state had experienced below-average precipitation, and reservoirs had been drawn down from average levels over the preceding drought years (U.S. Water News Online, 2005a). Especially hard hit were senior surface water users in the Snake River watershed of south-central Idaho (Figure 6).

Though wetter weather was on the forecast, Idaho water users did not relax. They knew that even if rainfall levels returned to normal, water sources in the state could take years to replenish. In addition, no one knew if the drought would break, or if it was one of the first signs of irreversible climate change (U.S. Water News Online, 2005b). Around the state, lack of water forced agriculturalists to reduce livestock numbers and farmers to cultivate only a fraction of their lands (U.S. Water News Online, 2005b; U.S. Water News Online, 2004). Surface waters were the first to diminish, while groundwater users continued to pump normal amounts of water out of the underground aquifers (Associated Press, 2001).

In response to junior groundwater rights users accessing pumped water for irrigation while the surface rivers dried up, seven south-central senior rights holders formed the Surface Water Coalition (SWC). The coalition members include the A & B Irrigation District, American Falls Reservoir District No. 2, Burley Irrigation District, Milner Irrigation District, Minidoka Irrigation District, North Side Canal Company, and Twin Falls Canal Company (U.S. Water News Online, 2007a). The latter is the largest canal company in the state. In 2005, the SWC took two actions to force the IDWR to provide them with water.

Figure 6: U.S. Geological Survey (modified). (1992). The Snake River Plain Regional Aquifer System. Retrieved 25 April, 2010, from http://pubs.usgs.gov/ha/ha730/ch_h/H-text8.html

First, in January 2005 the SWC claimed that groundwater users were sucking up their constitutionally given water and called on the IDWR to fulfill their senior rights by curtailing junior groundwater use so that surface water sources could recharge (Snyder, 2006a). Upset at the prospect of providing water for recharge in a time of shortage, groundwater users questioned whether surface users had actually suffered any material injury to their water rights (Dunlop, 2006). Proving "injury" is central to Idaho's conjunctive management laws, and must be established before a call for curtailment by junior water users can be answered. The director of the IDWR agreed that the surface water users had suffered injury, which he calculated to be 133,400 acre-feet of water in 2005. The IDWR ordered groundwater users to come up with the first 27,700 acre-feet of replacement water during the 2005 season (Dunlop, 2005).

The surface water users, upset that IDWR was not partitioning them as much water as they felt they deserved under their prior appropriation rights, responded by arguing that the conjunctive management rules requiring them to prove they were experiencing material injury were unconstitutional. In August of 2005 five members of the SWC—the American Falls Reservoir District No. 2, A & B Irrigation District, Burley Irrigation District, Minidoka Irrigation District and the Twin Falls Canal Co. —sued the IDWR about the constitutionality of conjunctive management (Dunlop, 2005).

Groundwater rights holders argued that the conjunctive management rules had already been established by the state government and should be upheld. Meanwhile, a representative of the SWC called the conjunctive management rules "bogus" and argued that when those rules were created, the senior surface rights holders "got short shrift in that deal" (Pence, 2005).

In June of 2006, the district judge ruled in favor of the surface water users, agreeing that indeed conjunctive management did violate the state of Idaho's constitutionally mandated prior appropriation. Groundwater users and the state of Idaho (via the IDWR) appealed the case to the state Supreme Court, which heard the case in December of 2006. At this hearing, which was referred to as Idaho's, "most important water-rights case in two decades," the Court argued that, "water would not be used for the public good if senior water-users [were] allowed to potentially hoard water that could be put to better use if allocated to junior users" (Environment and Energy Publishing, LLC, 2006).

The hearings continued through the winter until, on March 5, 2007, the Idaho Supreme Court granted the IDWR, "discretion in allocating water resources, rather than going solely by first-come, first-served water rights. The court ruled in favor of the state's contention that its conjunctive water management policy, which conflicts with the state's prior allocation doctrine, is constitutional"

(Environment and Energy Publishing, LLC, 2007). The state decided that even those with senior water rights must have limits on what they can access in times of drought. Those limits are up to the determination of the IDWR and must be connected to reasonable and beneficial uses of the water.

Surface water rights holders considered the decision a “deflating loss” (Times-News editorial board, 2007). They complained of delays associated with conjunctive management, including, “the burden of proof that saddles senior users far beyond that of junior users, and the lack of any time frame to settle water calls in a water season” (Times-News editorial board, 2007). Meanwhile, groundwater users were relieved that the state upheld the conjunctive management rules, essentially protecting them from having to give up too much water to the surface users. However, the SWC’s 2005 call for curtailment was still standing, requiring that groundwater pumpers divert water to senior users.

The state Supreme Court may have answered questions about the rules for managing water in Idaho, but the burden of deciding how much water to release or curtail when and where still rested in the hands of the IDWR who quickly set to work planning distribution of the little water in the state. Just a few short months after the Supreme Court decision, the IDWR picked up calls for groundwater curtailment that had been issued in 2005 by Blue Lakes Trout Farm and Clear Springs Food's Snake River Farm (U.S. Water News Online, 2007b). The IDWR threatened to curtail groundwater pumping unless mitigation could be achieved (U.S. Water News Online, 2007b). In the past, groundwater users had avoided curtailment orders by voluntarily sending some of the water they pumped from the ground into surface water sources. In this case, however, the low snowpack and forecasted drought had put water at such a shortage that groundwater users could not afford to send it away (U.S. Water News Online, 2007b). At the last moment, groundwater users avoided the curtailment by leasing water through the IDWR from water rights holders below Milner Dam and exchanging the leased water for release from reservoirs (Idaho Water Resource Board, 2005).

As water shortages continue, groundwater users are unhappy about the amount of water they are asked to give up, while surface water users are unhappy because they are not getting enough water to conduct their own agriculture or maintain trout farms. In light of these conflicts, litigation has continued. As each year goes by water levels in the state’s aquifers have gone down, increasing the risk of curtailment for groundwater pumpers. Meanwhile, IDWR continues to encourage mitigation and collaboration, hoping to avoid curtailment altogether (Poppino, 2008). One way for groundwater users to mitigate is to join the Idaho Ground Water Appropriators. This allows all groundwater users to work as a group to find money and water sources to pay back the water they take from the aquifer. As long as the water is replaced, they will not be curtailed (Poppino, 2008).

Just last October, IDWR issued a curtailment warning for the Eastern Snake Plains Aquifer in south-central Idaho for the summer of 2009. The warning is a response to calls from Clear Springs Foods, Inc. (which raises fish at a Snake River Farm facility), Blue Lakes Trout Farm, Inc., and the SWC, all three of whom hold senior water rights (Otter & Tuthill, 2008). To avoid this curtailment, groundwater users must cross their fingers for a large snowpack or seek out some new kind of mitigation to replenish any water they hope to withdraw over the coming year. One thing that both ground and surface water rights holders have agreed on is that they would like to see the aquifer replenished to original levels (Dunlop, Idaho water, 2005). In 2007, IDWR developed plans that would call for diverting nearly 30,000 acre feet of water from the Snake River into a network of channels in the hope that the water would seep through the channel beds and filter into and raise the level of the aquifer (U.S. Water News Online, 2007c). Indeed, when flow rates were measured that October, engineers found that water quantities diminished as measurements were taken farther downstream indicating that was water seeping out of the canals (Christensen, 2007). What they still don't know, however, is whether the water for sure reached the aquifer, and if so, how long it would take to flow through the aquifer and show up at other sites where it will again be available to surface water users (Christensen, 2007).

Idaho: Challenges for the Future

In 2008 the State Legislature created a Comprehensive Aquifer Planning and Management Program (CAMP) and an Aquifer Planning and Management Fund (Idaho Department of Water Resources, 2009). In light of declining aquifer levels, reduced spring and river flows, and a number of lawsuits, the IDWR created an Eastern Snake Plain Aquifer (ESPA) (Figure 7) Advisory Board in 2008 to draft a plan. The plan marks an effort to adjust water supply and demand in the ESPA over the long term and to identify opportunities to manage the available water to meet current and future water needs (Berg, 2008). With large budgets, long-term working timeframes, and collaborative management practices, water users in Idaho hope that these programs will help rejuvenate the diminishing aquifers of the state, in turn replenishing the cold-water springs that feed the surface water sources (Berg, 2008).

Figure 7: U.S. Geological Survey. Discharge of the Eastern Snake River Plain aquifer from basalt cliffs above the Snake River gorge. Retrieved June 16, 2009, from http://water.usgs.gov/lab/chlorofluorocarbons/research/snake_river/.

Colorado

Colorado Overview

Colorado adheres to the doctrine of prior appropriation for both surface and groundwater. Specifically, groundwater management is dependent upon whether the groundwater lies within a non-designated, designated or Denver groundwater basin. In “non-designated groundwater basins” there is a rebuttable presumption that the groundwater is “tributary,” such that surface and groundwater adheres to a single set of priorities. (Colorado Revised Statutes § 37-92-102, 2008). In “designated groundwater basins,” groundwater withdrawal permits are issued if there is still unappropriated and such new appropriation will not cause impairment (*Fundingsland v. Colorado Ground Water Commission*, 1970). Finally, in “Denver groundwater basins,” groundwater withdrawal permits are only approved for overlying owners contingent upon the requirement that no more than 1% of the underlying water may be extracted in any given year (Colo. Rev. Statute § 37-90-137(4), 2008)(Figure 8).

Figure 8: U.S. Fish and Wildlife Service, Rocky Mountain National Park. Retrieved April 26, 2010 from http://www.fws.gov/ficmnew/Proceedings%20on%20the%20Web/photo_gallery.htm

Colorado Constitutional Provisions

Article XVI § 5 of the Colorado constitution declares that (Figure 9) “water of every natural stream is…property of the public subject to appropriation.” Article XVI § 6 states that “the right to divert unappropriated waters of any natural stream to beneficial uses shall never be denied” and “priority of appropriation shall give the better right,” except that “water for domestic purposes” shall have preference. Thus, Colorado is a priority of appropriation state according to its Constitution.

Colorado Groundwater Management

The doctrine of prior appropriation applies to both ground and surface water in Colorado. Groundwater is defined as “any water not visible on the surface of the ground under natural conditions” (Colorado Revised Statute § 37-90-103(19), 2008). The Water Right Determination and Administration Act of 1969 (hereafter referred to as “the 1969 Act”) furthered the oversight of groundwater use by creating water divisions, each encompassing a major river watershed Colorado Judicial Department). Each division has its own water court, which is part of the state judicial system and determines all water rights, administers the buying and selling of water rights, and otherwise oversees the use and distribution of water (Colorado Judicial Department). The water court includes a division engineer overseen by the State Engineer and a water judge assigned by the state Supreme Court (Colorado Judicial Department). Groundwater regulation in Colorado largely depends upon whether the groundwater is located in a non-designated, designated or Denver groundwater basin.

In non-designated groundwater basins, groundwater that is “tributary water” is administered under a single set of priorities with surface water (Colorado Revised Statute § 37-92-102, 2008). All groundwater in non-designated basins is presumed to be “tributary” (Bryner and Purcell, 2003). However, this presumption may be rebutted if the water is determined to be “non-tributary groundwater” (Bryner and Purcell, 2003). “Non-tributary groundwater” is groundwater that will not deplete the surface flow at a rate of 0.1% or less than the rate of groundwater withdrawal (Colorado Revised Statute § 37-90-103(10.5), 2008). For example, if a potential groundwater user wishes to extract 1000 gallons per minute (gpm), then in order for that groundwater to be considered non-tributary, the groundwater user must prove that the surface flow will be depleted by no more than 1 gpm.

If the groundwater is “tributary water,” then the state engineer issues permits for new wells and regulates extraction according to the priority system (Bryner and Purcell, 2003). In order for the permit to be approved, the applicant must show that there is still unappropriated water available and that he will put the water to a beneficial use (Bryner and Purcell, 2003). Water courts have jurisdiction over both surface and tributary groundwater (Bryner and Purcell, 2003).

If the groundwater is “non-tributary groundwater,” then priority of appropriation does not apply (Colorado Revised Statute § 37-90-102(2), 2008). Rather, the resource is allocated based upon ownership of the overlying land (Colorado Revised Statute § 37-90-102(2), 2008). “Economic development of (non-tributary groundwater) shall allow for reduction of hydrostatic levels and aquifer water levels” (Colorado Revised Statute § 37-90-102(2), 2008). Rights may be decreed by water courts based upon a hundred-year aquifer life, overlying land ownership and withdrawal rates not to exceed 1% per year (Colorado Revised Statute § 37-90-137(4), 2008). The state engineer issues permits for “non-tributary” wells and a permit is required before drilling.

Colorado has “designated groundwater basins,” wherein “groundwater withdrawals have constituted the principal water usage for at least fifteen years preceding such proposed designation” (Colorado Revised Statute § 37-90-103(6)(a), 2008). The Groundwater Commission has jurisdiction over these basins and any person wishing to appropriate these waters must seek a permit from the commission (Colorado Revised Statute § 37-90-107(1), 2008). In these basins, permits are granted if there is still unappropriated water and the proposed well will not create “impairment” (*Fundingsland v.*

Colorado Ground Water Commission, 1970). What constitutes "impairment" is defined by the applicable designated groundwater basin (Colorado Code Regulations § 402-4, 2008). However, a permit that does not meet the guidelines of the designated groundwater basin may still be approved if there is a "replacement plan" (Colorado Revised Statute § 37-90-103(12.7), 2008).

"Not Non-Tributary Groundwater" is water in the Dawson, Denver, Arapahoe and Laramie-Fox Hills aquifers that fails to satisfy the definition of "Non-Tributary Groundwater (Colorado Revised Statute § 37-90-103(10.5), 2008)." Permits to appropriate these waters are issued by the water courts. These permits must include augmentation plans that, if needed, provide replacement water in order to prevent injury to senior water users (Bryner and Purcell, 2003). Overlying owners may withdraw groundwater from these aquifers and annual withdrawals may not exceed 1% of the available water underneath the owned land (Colorado Revised Statute § 37-90-137(4), 2008).

Colorado: Conflict between Surface and Groundwater Users

The most telling example of Colorado's issues with conjunctive management of surface and groundwater is set in the South Platte River Basin in the northeast corner of the state. Conjunctive water management was implemented in Colorado in a series of legislation passed in the 1960s and 70s. For the first time, the Colorado Ground Water Management Act of 1965 required groundwater users to apply to the State Engineer for a permit before drilling a well (Colorado Division of Water Resources (CDWR), 2007). Permitted wells were not subject to the priority rules that distribute surface water, but the State Engineer could deny a drilling permit if no unappropriated water was available or if drilling the well would cause material injury to senior water rights holders (Colorado Division of Water Resources, 2007). In 1968 two different studies both found that declining stream flows could be attributed to groundwater wells taking water over the preceding decade (Colorado Division of Water Resources, 2007).

Colorado: Outcomes and Challenges

The Water Right Determination and Administration Act of 1969 (hereafter referred to as "the 1969 Act") furthered the oversight of groundwater use by creating water divisions, each encompassing a major river watershed (Colorado Judicial Department). Division #1, the South Platte Water Division covers the northeast quarter of Colorado from the continental divide to the Nebraska/Kansas border and from the Wyoming border extending south past Denver (Wolfe, 2007)(Figure 9).

The 1969 Act called for an adjudication of all groundwater wells to be completed by the water courts before 1972. The adjudication would compile the information needed to determine priority of existing wells, so that groundwater could be entered into the prior appropriation system and the water courts could administer its distribution (Colorado Division of Water Resources, 2007). This met with much resistance from groundwater users because they had the most junior rights in the priority system and would be subject to water calls from senior rights holders. The 1969 Act allowed junior groundwater users to continue to pump water during a call as long as they filed a water-court-approved augmentation plan (Colorado Division of Water Resources, 2007).

Figure 9: U.S. Geological Survey. South Platte River Basin. Retrieved 26 April 2010 from: http://co.water.usgs.gov/nawqa/splt

In the South Platte River Basin an augmentation plan is, "a plan that acknowledges and quantifies depletions caused by well pumping, identifies sources of water that can be used to compensate for the out-of-priority depletions caused by well pumping, and outlines an approach to use the replacement water to replace out-of-priority depletions to the stream such that no other water right is injured" (Colorado Division of Water Resources, 2008).

In the 1970s, the State Engineer encouraged groundwater users to form coalitions, reasoning that large groups could more easily acquire funds and water for augmentation (Colorado Division of Water Resources, 2007). Two main coalitions were formed in the South Platte Water Division: Groundwater Appropriators of the South Platte (GASP) and Central Colorado Water Conservancy District's Groundwater Management Subdistrict (Central GMS) (Colorado Division of Water Resources, 2007). GASP and Central GMS submitted annual substitute water supply plans (SWSPs) to the State Engineer outlining how they planned to augment any water draw downs that could injure senior rights holders. The SWSPs were temporary versions of the more permanent "augmentation plans" described in the 1969 Act.

Everything went well for about 3 decades as water was abundant. Calls only occurred in late summer, if ever, and were easily augmented. The State Engineer continued to approve SWSPs submitted by the groundwater coalitions in the South Platte River Basin. In the 90s the State Engineer wrote to GASP and Central GMS that they should stockpile water in preparation for a possible drought (Colorado Division of Water Resources, 2007). GASP did not respond to the warning while Central GMS, which had a larger revenue base, did heed the Engineer's warning and saved some water.

In 2002, two important things happened that disrupted the smooth functioning of the water distribution system in the South Platte Water Division. First, an argument in the district civil court about land access turned into a dispute over water, and both the district water court, and later the state Supreme Court found the State Engineer had no judicial authority to approve the temporary SWSPs in place of water-court-approved augmentation plans as he had done for the past thirty years (Colorado Division of Water Resources, 2007). Instead, well organizations in the South Platte Water Division were given three years to submit augmentation plans to the water court (Colorado Division of Water Resources, 2007). The State Engineer could continue to approve or deny SWSPs as long as they were attached to augmentation plans under review by the water courts (Colorado Division of Water Resources, 2007). Second, Colorado experienced the worst drought year on record, causing a severe shortage of water among surface and groundwater users in the South Platte Water Division (Colorado Division of Water Resources, 2007).

In the face of the water shortage, controversy flared up. Senior surface water rights holders made calls early in the summer that lasted the rest of the year and continued through the following years. When GASP was unable to catch up on its augmentation, its SWSP for 2003 was not approved and the approximately 3,000 wells were not allowed to pump. GASP went out of business while Central GMS could barely lease enough water to fulfill its SWSP. Eventually a new groundwater coalition, the Well Augmentation Subdistrict (WAS) was formed out of members of GASP and other groundwater pumpers. WAS and Central GMS both compiled augmentation plans and submitted them to the water court in 2003 (Colorado Division of Water Resources, 2008).

While these augmentation plans were under review, the SWSPs for WAS in 2004, 2005, and 2006 were approved by the State Engineer. However, senior water rights holders appealed those SWSPs in spring of 2006 and the courts found they had indeed provided inadequate augmentation for the water they were using (Simpson, 2006). Snowpack was below average, and water that had been used for augmentation in the past was no longer available as it had been diverted to other uses (Simpson, 2006). By the summer of 2006, the 449 WAS wells were ordered not to pump until further notice (Simpson, 2006). These cases are still under review in the courts, and the last two summers have seen severe pumping restrictions that have been detrimental to agriculture in the South Platte River Basin. For example, the 2006 pumping curtailments resulted in loss of agriculture from 30,000 productive acres (Howe, 2008). At the same time, "the South Platte River had a shortage of about 15,000 acre-feet of water due to the delayed effect of Central WAS wells having pumped water in previous years under augmentation plans approved by the State Engineer" (City of Boulder, 2008).

Colorado Outcomes and Challenges for the Future

The conflict over conjunctive management in the South Platte River Basin raises two main issues surrounding water users' avoidance of the Colorado water court system. First of all, groundwater coalitions avoided adjudication by the water court by filing annual SWSPs with the State Engineer rather than applying for augmentation plans. This turned into a disaster when drought hit and the State Engineer continued to approve SWSPs that offered inadequate augmentation (City of Boulder, 2006). Now the South Platte River Basin is in a situation where hundreds of wells are ordered not to pump, downstream users are not finding as much water as they should in the river, and, as the calls of downstream senior rights climb higher through the appropriation system, municipalities like Boulder are having to give up water because the pumpers are unable to do so (City of Boulder, 2008). This problem has been addressed by the courts denying the State Engineer the authority to approve SWSPs.

The second, yet related, problem is that the exchange of water rights is stymied by having to pass through the water court, thus preventing efficient allocation of water in the South Platte River Basin (Howe, 2008). The way prior appropriation and water rights are supposed to work is that the senior rights get traded in a market to the highest value uses. (Figure 10) In the South Platte River Basin, the cities of Boulder, Greeley, and Highlands Ranch are considered higher value uses than agriculture and hold rights that are senior to agriculture supplied by pumping, but junior to downstream agricultural uses (Howe, 2008).

Figure 10: South Platte River, Weld County, Colorado. Retreived 26 April 2010 from: http://photokayak.fit2paddle.com/south-platte-river/

Charles Howe, Emeritus Professor of Economics at the University of Colorado, Boulder, and a team member of Western Water Assessment, argues for a water bank system to ameliorate this second problem. He writes, "In most western states, 'water banks' are being used to facilitate leases and permanent transfers [of water rights]. These programs, administered by each state, serve as clearinghouses or brokers, connecting buyers and sellers. … Greater use of the several forms of water banks will significantly reduce the ongoing conflicts between the traditional administration of water rights and the emerging need for greater flexibility and economic efficiency in western water administration" (Howe, 2008).

Washington

Washington Overview

In Washington, both surface and groundwater are subject to the doctrine of priority appropriation. Any person seeking to appropriate either surface or groundwater must seek a permit from the Washington Department of Ecology, unless an exception under Wash. Rev. Code § 90.44.050 applies (Revised Code of Washington § 90.44.050, 2008). If WDE determines that there is a "hydraulic continuity" between ground and surface water, then such waters must be managed under a single set of priorities (Washington Administrative Code § 173-549-060, 2008). A "hydraulic continuity" exists when groundwater withdrawal has at least a de minimis effect on surface water flow (*Postema v. PCHB*, 2000). No actual effect need be measured through standard measuring equipment; rather WDE may determine "hydraulic continuity" through acceptable scientific methods such as three-dimensional computer modeling (*Postema v. PCHB*, 2000). (Figure 11)

Figure 11: Washington Rivers Map from Geology.com. Retrieved 26 April, 2010 from http://geology.com/state-map/washington.shtml

Washington Constitutional Provisions

There is only one constitutional provision related to water in Washington's Constitution. Article XXI Section 1 states that "the use of the waters of this state for irrigation, mining, and manufacturing purposes shall be deemed a public use" (Washington Constitution, Article 21 § 1). Thus, Washington's State Constitution provides no guidelines to how water, determined to be a public use, should be managed and regulated.

Washington Groundwater Management

In Washington, both ground and surface waters are subject to the doctrine of prior appropriation. Accordingly, groundwaters in Washington "belong to the public and are subject to appropriation for beneficial uses" (Revised Code of Washington § 90.44.040, 2008). Groundwater is defined as "all waters that exist beneath the land surface or beneath the bed of any stream, lake or reservoir…whatever may be the geological formation or structure in which such water stands or flows, percolates or otherwise moves (Revised Code of Washington § 90.44.035(3), 2008)."

A permit is required to appropriate both ground and surface water. Potential appropriators must file a permit application with the Washington Department of Ecology (WDE) (Revised Code of Washington § 90.44.050, 2008). However, no withdrawal permit is necessary for stock-watering, watering of a lawn or non-commercial garden not exceeding one-half acres, domestic uses not exceeding 5,000 gallons per day and industrial purposes not exceeding 5,000 gallons per day (Revised Code of Washington § 90.44.050, 2008). Applications for permits must meet all the requirements of the surface water statute, Revised Code of Washington § 90.03.25 (2008), as well as the requirements of the groundwater statute, Revised Code of Washington § 90.44.060 (2008). If the WDE determines that there is water available for appropriation, such appropriation is for a beneficial use and such appropriation will not impair existing rights, then the application for permit is granted (Revised Code of Washington § 90.44.290, 2008).

WDE has the authority and discretion to limit withdrawals in a particular groundwater basin "to an amount that will maintain and provide a safe sustaining yield" (Revised Code of Washington § 90.44.130, 2008). If the total available withdrawal supply is "inadequate for the current needs of all holders of valid rights," "such decrease shall conform to the priority of the existing rights" (Revised Code of Washington § 90.44.180, 2008).

Washington's groundwater code recognizes the potential interconnectivity of ground and surface waters (Revised Code of Washington § 90.44.030, 2008). As such, when ground and surface waters are determined to be to be in "significant hydraulic continuity," both the ground and surface water rights must fall under one appropriation scheme (Washington Administrative Code § 173-549-060, 2008; *Rettkowski v. Department of Ecology*, 1993). (Figure 12) "Significant hydraulic continuity" exists if the WDE determines that a proposed or existing groundwater withdrawal has or will have "a direct and measurable impact on stream flows" (Washington Administrative Code § 173-510-050, 2008). In determining whether there is a "direct and measurable impact," any de minimis impact on the surface flow is sufficient (Washington Administrative Code § 173-510-050, 2008). Furthermore, WDE does not need to show an actual decrease in surface flow by groundwater pumping through standard measuring devices; rather, WDE may "use new information and scientific methodology as it becomes available and scientifically acceptable for determining hydraulic continuity" (Washington Administrative Code § 173-510-050, 2008). Currently, WDE maintains that a three-dimensional computer model is the best method for determining hydraulic continuity (Washington Administrative Code § 173-510-050, 2008).

Washington recognizes minimum stream flows. These flows were established by WDE, pursuant to the Water Resources Act of 1971, Wash. Rev. Code § 90.54.040 (2008). These minimum flows constitute an appropriation with a priority date of the effective date of the rule establishing such minimum flow (Revised Code of Washington § 90.03.345, 2008).

Figure 12: Camas Washougal Chamber of Commerse. The Columbia River Gorge National Scenic Area. Retreived 26 April 2010 from http://www.cwchamber.com/cwdata/Portals/0/the gorge.jpg

Thus, in determining whether to approve a permit to withdrawal groundwater, WDE must determine whether established minimum flows would be affected by the proposed use (Revised Code of Washington § 90.03.290, 2008). If the answer is yes, then the application must be denied.

In summation, WDE must adhere to a single set of appropriation dates for ground and surface waters if it determines that groundwater pumping will decrease the surface flow, even if that diminishment is de minimis. WDE can use acceptable scientific methods for determining ground and surface water interconnectivity and currently it utilizes a 3-d computer model. Any application to withdraw groundwater that will impair existing surface or groundwater rights or reduce minimum flows must be denied.

Washington: Conflict between Surface and Groundwater Users

Three cases that took place in the 1990s and early 2000s in Washington highlight the strengths and weaknesses with the state's water management system and provides context for issues Washington water users struggle to overcome today: *Rettkowski v. Department of Ecology* (1993), *Hubbard v. State of Washington* (1997), and *Postema v. Pollution Control Hearings Board* (2000). Each of these cases dealt with questions of defining connectivity between ground and surface waters and clarifying how to distribute the water to different rights holders.[1]

Washington's surface water code was written in 1917 and distributes water according to prior appropriation. The Groundwater Code of 1945 was meant to supplement the Surface Water Code and incorporate groundwater into the prior appropriation system. Importantly, the Groundwater Code says that new permits for water withdrawal are not allowed if they will impair existing surface water rights.

Washington: Outcomes and Challenges

A number of legal challenges over water management in Washington provide several examples

[1] According to one person interviewed, in Washington, the term "conjunctive management" refers to a water supply utility that owns both surface and groundwater resources and manages them together for maximum efficiency by withdrawing surface water during wet periods and groundwater during dry periods. There is not a single term used to refer to the state's management of ground and surface waters together under one appropriation system. Rather, the state refers to "connectivity" or "continuity" between ground and surface waters

of the challenges associated with managing surface and groundwater resources.
Rettkowski v. Department of Ecology

Surface water rights in the Sinking Creek Basin of eastern Washington's Lincoln County are about 80 years senior to the first groundwater permits, which were issued in the 1950s (*Rettkowski v. Dept. of Ecology*, 1993). Starting in the 1960s, ranchers in Lincoln County who used surface water from Sinking Creek to water their livestock complained that irrigators were diminishing surface water supplies by pumping groundwater (*Rettkowski v. Dept. of Ecology*, 1993). Ecology eventually responded to the ranchers' concerns by conducting two studies, both of which found that the withdrawal of groundwater was negatively affecting surface water supplies (*Rettkowski v. Dept. of Ecology*, 1993). Even so, five more years would pass before, late in the summer of 1990, Ecology finally responded to the ranchers' complaints by issuing an order for irrigators to "cease and desist" groundwater pumping in the Sinking Creek Basin (*Rettkowski v. Dept. of Ecology*, 1993).

Rettkowski, whose well had been part of one study, and other irrigators sided against Ecology and the ranchers who called for the shutdown in a case known as *Rettkowski v. Department of Ecology*. The irrigators demanded that Ecology not issue any orders until an adjudication of the water rights was completed for the Sinking Creek Basin, arguing that Ecology did not have authority under the state constitution to order the shutdown, that the order was invalid, and that the irrigators had been denied a chance to defend their water rights in court (*Rettkowski v. Dept. of Ecology, 1993*).

In Washington state, "A general water right adjudication is a legal process conducted through the State Superior Court that determines the validity and extent of existing water rights in a given area" (Washington Dept. of Ecology, n.d.). The adjudication is treated like a regular trial in which those seeking water rights are defendants and Ecology is the plaintiff (Washington Dept. of Ecology, 2009). The adjudication determines the priority date, purpose of use, quantity of water, point of diversion, place of use, and any limitations to each water right in a given basin (Washington Dept. of Ecology, 2006). Although Ecology can instigate an adjudication, it has no authority to conduct the actual determination of water rights based on its own study. That power rests within the courts, not the agency. This process is designed to ensure that everyone involved has an opportunity to present evidence supporting their own water rights during the adjudication process.

The Supreme Court made its decision in September of 1993, siding with the irrigators in declaring that based on the constitutional rules, Ecology has no authority to determine water rights, nor can Ecology enforce rights that have not undergone a general adjudication by the Superior Court in the county where the water is located. They agreed that the purpose of adjudication is to ensure that water rights are determined in courts where each party has an opportunity to present evidence and argument in support of its own water rights.

In *Rettkowski v. Department of Ecology*, two judges dissented the majority opinion. They argued that Ecology has authority to issue permits without adjudication, but as soon as the permit is issued Ecology has no authority to regulate the water withdrawal (*Rettkowski v. Dept. of Ecology*, 1993). The dissenting judges wrote,

> if a week [after issuing a permit] it became clear that water use under the permit was impairing a senior right, Ecology could not act to protect the senior water user because that would constitute an adjudication of the water rights involved. That is an absurd result

and should be avoided. (*Rettkowski v. Dept. of Ecology*, 1993)

According to one expert who was involved with this case, the legislature should have moved in immediately and fixed the problem of Ecology's lack of authority over its own permits, but they never did. Now rather than having to take responsibility for the permits they issue Ecology can say, "We don't have the jurisdiction to take care of these problems so it's not our fault."

In addition, the dissenters wrote that the adjudication solution offered was "prohibitively expensive," writing that, "interminable litigation is what the majority has fashioned as a solution, and to no purpose. … [A] general adjudication … is now the only relief which the majority opines is available" (*Rettkowski v. Dept. of Ecology*, 1993). To this date, over 15 years after the *Rettkowski v. Department of Ecology* decision, there are about 170,000 unadjudicated water claims in the state (Washington Dept. of Ecology, 2009).

Because so many of the water resources in the state have not been adjudicated, no one really knows how much water is available, who has the senior claims, or whether water actually exists to fulfill all of the claims that are held (Washington Dept. of Ecology, 2009). These gaps in information can limit the capacity to plan for water management and cause senior water rights to go unrecognized (Washington Dept. of Ecology, 2009).

Hubbard v. State of Washington

Between 1979 and 1992, two brothers James and John Hubbard bought land, planted orchards, and applied for well permits for irrigation in the Wagonroad Coulee, a valley near the Okanogan River. While investigating the Hubbards'(Figure 13) permit applications in 1992, Ecology determined there was significant continuity between the Wagonroad Coulee Aquifer and the Okanogan River. Ecology granted permits for withdrawal of specified amounts of water from the Hubbards' wells for beneficial uses such as irrigation and frost protection under the condition that the wells would have to be shut down whenever the Okanogan River fell below its minimum instream flow (*Hubbard v. State of Washington*, 1997).

In Washington, "minimum instream flows" are essentially surface water rights for a specific amount of water that must remain in the rivers. Minimum instream flows first came about as part of the Water Resources Act of 1971, and are treated just like any other water appropriation with a priority date of their date of establishment. The minimum instream flow for the Okanogan River was established in 1976, and has priority over subsequent water rights appropriators, such as the Hubbards. If groundwater has significant hydrologic continuity with the surface water in the river, those permits are subject to the same restrictions as permits for surface water withdrawals from that resource, which in this case is a prohibition against withdrawing water during periods of low instream flow (*Hubbard v. State of Washington*, 1997).

The Hubbards appealed their conditional water permit, claiming there is no significant continuity between their aquifer and the river. They contend the Board was wrong in concluding that the Okanogan River's minimum instream flow is senior to their rights and that a significant continuity exists between the underground water source of their wells and the river (*Hubbard v. State of Washington*, 1997).

Figure 13: Washington Wildlife and Recreation Coalition, Methow Farmland, Okanogan County, WA., Retrieved 26 April 2010 from http://www.wildliferecration.org/wwrp-projects/projects/Farmland_Preservation

This case was heard by the Third Division Court of Appeals in Washington, who decided that the term "significant" applies only to the continuity between the ground and surface water, not to the effects of the withdrawals. Because the effects of pumping groundwater will eventually reach the river there is significant continuity no matter whether the "use" (in this case 0.004% of the river) is significant or not. In addition, the court held that, "Any effect on the river during the period it is below the minimum instream flow level conflicts with existing senior rights (such as the minimum flow level itself) and may be reasonably considered detrimental to the public interest" (*Hubbard v. State of Washington*, 1997). In conclusion, the court decided that the conditional permits granted by Ecology were reasonable.

Postema v. Pollution Control Hearings Board

Following the Hubbard decision, Ecology continued to deny groundwater withdrawal permit applications in watersheds where the groundwater is in hydraulic continuity with surface water where minimum instream flows are not met for a substantial part of the time or where surface water sources are closed to further surface appropriation. In 1995 and 1996 Ecology denied over half of about 600 water permit applications due to unmet minimum instream flows.

Eventually, five of the cases were consolidated and reached the Supreme Court as *Postema v. Pollution Control Hearings Board* (PCHB) (2000). The groundwater users reasoned that Ecology had no authority to deny a groundwater application if effects on the surface waters were not measurable, arguing that, “hydraulic continuity alone is an insufficient ground for denial” (*Postema v. PCHB*, 2000).

The decision of the Supreme Court including the following responses:

1)Minimum instream flows are not limited water rights that may be overridden

2)A groundwater permit may be denied even if direct and measurable impact on surface water using standard stream measuring devices has not been shown

3)An application for a permit to withdraw groundwater must be denied if “it is established factually that withdrawal will have any effect on flow or level of surface water”

4)Denial of a groundwater appropriation permit must be based on a finding of actual, not just possible, impairment of minimum surface water flows

Washington has made great progress in using its courts to clarify the application of its ground and surface water management rules and laws, but only proper adjudication can provide the complete information necessary for thorough and precise management of Washington water supplies.

One adjudication process in the Yakima Basin has been ongoing for over 30 years and has come before the state Supreme Court twice (*Rettkowski v. Dept. of Ecology*, 1993). Meanwhile, only 10% of the land area in Washington State has been adjudicated (Unger, 2007). In 2005 and 2006 bills proposing water courts as an entity that could facilitate water adjudications were raised in the state legislature, but died both years (Unger, 2007.)

In 2005, minutes from the Washington State Board for Judicial Administration indicated that the establishment of water courts was a low priority in the state legislature and that concerns had been raised about the selection and terms of water judges as presented in the bill (Cryderman, 2005).

An adjudication has still not been conducted in the Sinking Creek Basin. The irrigators may have won the argument for adjudication in 1993, but water use still goes unregulated as the adjudication is pending. Ranchers feel that their senior rights have been ignored by the authorities. One Sinking Creek rancher talked to a news reporter in 1993: “‘It’s first in time, first in right,’ he says through clinched teeth. ‘Do I get mad when I think about it? You're damn right I do’” (Wallace, 1993). On the other hand, irrigators believe that when the adjudication is conducted, “the ranchers may find they don't have as much right to the water as they think” (Wallace, 1993).

Washington: Challenges for the Future

Ecology has made modernization of water rights adjudication a legislative priority in 2009 (Washington Dept. of Ecology, 2009). Already the department has published documents outlining plans to streamline and simplify the adjudication process such as by allowing small adjudications rather than basin-wide, promoting use of conference calling and mail rather than person to person negotiations, and encouraging “courts to direct parties toward alternative dispute resolution” (Washington Dept. of Ecology, 2009).

However, other problems exist that will also need to eventually be sorted out by the courts. For example, in Washington, any well that pumps less than 5,000 gallons per day of water is exempt and does not require a permit from Ecology. According to a water expert interviewed at Ecology, “In areas where the water if fully appropriated and many of these wells go in, they are cumulatively stealing water from senior right holders. It is just a matter of time before we will have a lawsuit about this.” Water management faces many challenges, especially as Washington’s population continues to grow and climate change reduces water supplies (Unger, 2007). Washington has an estimated 0.5 million wells with about 8,000 wells being added per year (Unger, 2007).

Arizona

Arizona Overview

Arizona separately manages its ground and surface water. Surface water is subject to Arizona's appropriation doctrine, while groundwater is subject to Arizona's groundwater code as established by the Groundwater Management Code of 1980 ("the Code"). Therefore, it is crucial to determine whether the water in question qualifies as ground or surface water. Groundwater is defined as "any waters under the surface of the earth, unless the water is flowing in an underground stream with ascertainable beds and banks" (Arizona Revised Statute § 45-101(5)). Unless the groundwater to be pumped is located in an Active Management Area (AMA) or an Irrigation Non-expansion Area (INA), the water may be extracted to the extent necessary for a beneficial purpose, regardless of its effect upon surface waters. Groundwater extraction in AMAs is limited to historical uses and a very limited list of activities for which a groundwater withdrawal permit may be granted (Arizona Revised Statute § 45-452). In an INA, only groundwater pumping for new irrigation purposes is limited (Arizona Revised Statute § 45-437).

Figure 14: U.S. National Park Service. Grand Canyon National Park, AZ. Retrieved July 16, 2009, from http://www.doi.gov/photos/highresolution/Grand%20Canyon%202.jpg.

Arizona Constitutional Provisions

Article XVII §§ 1-2 of Arizona's State Constitution establishes that "riparian water rights" will not be recognized in Arizona and that all "existing rights to beneficial uses of water" shall be recognized (Arizona Constitution, Article XVII §§ 1-2). In other words, Arizona's Constitution basically sets forth that appropriation is the guiding doctrine and that beneficial uses of water are necessary for an appropriation of water. Arizona has further codified that "the waters of all sources…belong to the public" and are subject to appropriation to be limited by beneficial use (Arizona Revised Statute § 45-141)

Arizona Groundwater Management

Arizona does not conjunctively manage its surface and ground waters (Bryner and Purcell, 2003, p. 7). Surface waters are governed by Arizona's doctrine of prior appropriation, and in order to appropriate surface water in Arizona, a user must file an application for a permit with ADWR (Bryner and Purcell, 2003, p. 7). Groundwater is defined as any waters under the surface of the earth, unless the water is flowing in an underground stream with ascertainable beds and banks (Arizona Revised Statute § 45-101(5)). Until 1980, the only regulation of groundwater law was the common law doctrine of "reasonable use" (Blomquist et al., 2001, p. 653). The reasonable use doctrine limits withdrawals to what is necessary for beneficial purposes. Water cannot be simply wastes and may not be transported off the land if it interferes with the rights of adjacent landowners. In 1980, Arizona enacted the Code in order to control overdraft conditions (Arizona Revised Statute § 45-101).

The Arizona Department of Water Resources (ADWR) is responsible for regulating and administering all laws relating to surface and groundwater (Arizona Revised Statute § 45-103). The director of ADWR has "general control and supervision" of surface and groundwater as well as authority to develop programs relating to the management, conservation and utilization of both surface and groundwater basins in this state (Arizona Revised Statute § 45-105).

The Code established three levels of water management: AMAs, INAs, and general statewide provisions. There are currently five AMAs (Arizona Revised Statute § 45-411). However, the director may designate a new area if necessary to preserve groundwater for the future, to prevent land subsidence or to prevent water degradation (Arizona Revised Statute § 45-412). The AMAs are the only basins in Arizona where groundwater rights have been quantified (Blomquist et al., 2001, p. 664). No new acreage may be irrigated in an AMA (Arizona Revised Statute § 45-452). In order to extract groundwater in an AMA, a person must have a grandfathered water right or a groundwater withdrawal permit to extract groundwater from a non-exempt well. Groundwater withdrawal permits in AMAs are limited to seven categories as set forth in Arizona Revised Statute § 45-512.

Grandfathered groundwater rights in the initial AMAs are determined by the groundwater use for the five-year period prior to 1980 (Staudenmaier, 2006, p. 19). Such rights are known as grandfather rights and fall within one of three categories: Irrigation Grandfathered Rights; Type 1 Non-Irrigation Grandfathered Rights; and Type 2 Non-Irrigation Grandfathered Rights (Bryner and Purcell, 2003, p. 9). "Irrigation Grandfathered Rights" are appurtenant to the irrigated lands and may not be transferred for use on other lands (Arizona Revised Statute § 45-465). "Type 1 Non-Irrigation Grandfathered Rights" arise from retired irrigation rights (Arizona Revised Statute § 45-464). These rights are valid if approved by the director in conformance with Arizona Revised Statute § 45-469. "Type 2 Non-Irrigation Grandfathered Rights" are based upon historic non-irrigation groundwater uses and may be sold, leased or moved within the AMA freely (Staudenmaier, 2006, p. 20).

The director may designate INAs if "there is insufficient groundwater to provide a reasonable safe supply for irrigation and current rates of withdrawal" and "establishment of an AMA is not necessary (Arizona Revised Statute § 45-432)." In an INA, only land that was legally irrigated in the prior 5 years to the INA's creation may be irrigated by groundwater, effluent, diffused water or surface water (Arizona Revised Statute § 45-437).

Arizona: Conflict between Surface and Groundwater Users

In contrast to the moister mountainous states of Idaho, Washington, and Colorado, Arizona has an arid climate and few headwaters. Most of Arizona's water consumption is taken from the Colorado River (39.8%) or groundwater aquifers (43.6%) (Arizona Department of Water Resources, 2009b). Arizona does not manage its surface and groundwater conjunctively. This has allowed for some benefits, such as one of the most forward-looking groundwater management programs in the United States, as well as some problems, including lack of protection for surface water sources that may be drawn down by groundwater withdrawals.

Arizona: Outcomes and Challenges

The Overdraft Problem

In Arizona, groundwater does not fall under the Prior Appropriation Doctrine and was pumped more or less without oversight throughout much of the state's existence. (Figure 15). Arizona has been taking more water from underground supplies than it was able to recharge, a situation known as overdrafting," since the 1940s (Jacobs). As can be guessed, there are several significant problems associated with overdrafting, including increased expense of drilling as wells must go deeper to reach the lowered water table, decreased water quality because deeper water tends to have more salts and minerals dissolved into it, and cracking and settling of surface lands as the support offered by underground water is removed (Arizona Department of Water Resources, 2009b). In addition, overdrafting is not sustainable for the long term as sources of water cannot replenish.

In response to these problems, Arizona passed the Groundwater Management Code of 1980 ("the Code"), which sought to address concerns about lowering aquifer levels throughout the state by taking control of overdraft issues, allocating the available groundwater resources, and creating plans to augment diminishing groundwater resources (Arizona Department of Water Resources, 2009b). In addition to creating the Arizona Department of Water Resources (ADWR) to administer groundwater management throughout the state, the Code describes three management approaches for groundwater resources: 1) general statewide provisions, 2) more specifically controlled Irrigation Non-Expansion Areas (INAs), and 3) the most rigorous Active Management Areas (AMAs). The Code addressed the state's attitude of promoting limitless development by creating a shift toward seeking sustainable water use practices. The main goal of the Code is to achieve "safe-yield" from aquifers by 2025, meaning water withdrawn will equal the water that is put into the aquifers (Arizona Department of Water Resources, 2009b).

As an example of how safe-yield might be achieved, the most rigorous water management occurs in Arizona's five AMAs. These are centered around and named after urban areas of the state where the largest water requirements exist: Phoenix, Pinal, Prescott, Tucson, and Santa Cruz (Arizona Department of Water Resources, 2009a). Although they span only a small portion of the state's surface area, the AMAs encompass the aquifers where 70% of the state's overdraft of groundwater resources has occurred. Under the Code, the AMAs seek to protect underground water resources in several innovative ways. Each of the five AMAs in the state has a detailed system of permitting and regulation outlined in a comprehensive management plan, which is updated every five to 10 years (Harvard University Kennedy School of Government, 2009).

Figure 15: Photo by Kepner, W.G. (U.S. EPA spearheaded by the Center for Biological Diversity). Riparian (cottonwood/ Goodding willow) San Pedro River Basin in southern Arizona for over ten years Hereford, AZ. Retrieved July 16, 2009, from (Shankerhttp://www.epa.gov/esd/land-sci/photo06.htm.

New irrigation is prohibited within the AMAs (Arizona Department of Water Resources, 2009b). Developers must demonstrate that a 100-year supply of water exists for any new subdivisions, housing, or other development and must apply to the ADWR for an assured water supply certificate, which they are required to publicize to potential purchasers of the development (Arizona Department of Water Resources, 2009b). Furthermore, wells must be metered and annual water withdrawal is carefully measured and reported, with penalties for anyone who uses unauthorized water (Arizona Department of Water Resources, 2009b). In addition to these provisions for groundwater management within AMAs, the Code creates programs to recharge aquifers by injecting surface water or treated wastewater underground for storage (Arizona Department of Water Resources, 2009a).

San Pedro River

One situation in particular illustrates the complexity of the conflict between surface and groundwater use and provides an example of the weaknesses of water law in Arizona. A collection of citizens and environmental groups spearheaded by the Center for Biological Diversity has fought the Arizona Department of Water Resources to protect water in the ecologically diverse San Pedro River Basin in southern Arizona for over ten years (Shankeret al., 2004).

The San Pedro River, which lies outside of a designated INA or AMA, provides habitat for over 300 bird species, including many that migrate between the United States and Mexico and two endangered species, as well as offers recreational opportunities (Davis, 2005; Bureau of Land Management, 2009). In 1998, the San Pedro Riparian National Conservation Area (RNCA) was created by Congress and was granted a water right consisting of 11,208 acre feet of water per year in the San Pedro River (Shanker et al., 2004). According to the Bureau of Land Management, “The primary purpose [of the San Pedro RNCA] is to protect and enhance the desert riparian ecosystem, a rare remnant of what was once an extensive network of similar riparian systems throughout the American Southwest” (Bureau of Land Management, 2009).

Along the San Pedro River, water managers face a paradox. The population at a military base called Fort Huachuca and the nearby municipality of Sierra Vista continue to grow, along with the numbers of new groundwater wells pumping to meet water needs for the growing population (Silver, 2005). Before 1993, the ADWR indicated that a 100-year supply of water did not exist in the basin and forced developers to share this information with purchasers, but after 1993, when water supplies were diminishing, ADWR approved water supply assurances for developers (Shanker et al., 2004). For several days in the summer of 2005, water stopped flowing in the San Pedro River (McKinnon, 2005). State agencies suggested various explanations for the halted water flow including spread of thirsty foliage along the riverbanks, late arrival of the summer rains, and drought (McKinnon, 2005). However, a representative of the environmental groups argued:

> There is a clear connection between the draining of the groundwater for subdivisions and the viability of the base flow of the San Pedro River. The state argued in court that ADWR does not have to consider impacts on the river or surface water when it makes an adequacy evaluation -- but that is tantamount to legally closing its eyes. In reality, the only way a 100-year supply of water in the Upper San Pedro Basin could possibly exist, is through the illegal denial of federal water rights and the resulting loss of the San Pedro River. (Shanker et al., 2004).

Over the following years, water flow stopped in the San Pedro River each summer before the rainy season started (Hess, 2007). One of the main responses to this conflict has come via the Upper San Pedro Partnership (USPP). The USPP is a group of private and governmental organizations with an interest in water and water management in the area that formed in 1988. One of the tasks of the partnership is to prepare each year, in collaboration with the Secretary of the Interior, a report outlining progress toward reducing overdraft and establishing safe-yield in the watershed surrounding the San Pedro River (Kempthorne & Myers, 2008, p. 3). This Congressional mandate came about to address issues of water reduction affecting listed endangered species in the San Pedro River. Though the San Pedro watershed still does not have the special management status of an AMA or INA under Arizona water law, the area receives much of the same attention in monitoring ground and surface water sources and limiting water use, as outlined in the annual reports to Congress.

Arizona: Outcomes

By carefully measuring water use and limiting new withdrawals of water, even if it means prohibiting some development, the Code has directed the state of Arizona toward a secure water supply in the future. In 1986 Harvard University gave the state of Arizona an Innovation in American Government Award, recognizing the progressive approach of the Groundwater Management Code to address issues of pressing public concern and welfare (Harvard University Kennedy School of Government, 2009). Furthermore, the Code was recognized by the Ford Foundation with a $100,000 grant to support enactment of the Code's provisions through creation of public awareness materials, high-school curriculum about water management, and staff training for ADWR hydrologists (Ford Foundation, 2009). The awards was emphasized that no other state had attempted to manage its water resources with such foresight and comprehensiveness (Arizona Department of Water Resources, 2009a).

However, despite the glowing accolades, inevitable problems still exist with water management in Arizona. Protection of water resources threatens to limit growth in some booming areas of the state, and ADWR has been accused of authorizing groundwater withdrawal for developers when the supply does not necessarily exist (Shanker et al., 2004). In addition, lawsuits have arisen disputing whether groundwater withdrawals affect surface water sources (Shanker et al., 2004).

Already in Arizona other rivers, including the Santa Cruz, which flows through Tucson, have dried up due to a combination of factors, which may include drought, overdrafting of water resources, and changing vegetation (Davis, 2005). Water law in Arizona does not recognize any connectivity between groundwater and surface water supplies. While some environmental and civilian groups claim groundwater withdrawals have diminished water in rivers threatening ecosystems and compromising some endangered species, developers claim drought has caused the disappearance of the water, and scientific uncertainty means proving a true cause/effect relationship between ground and surface water is difficult (Glennon, 2002).

Arizona: Challenges for the Future

To address the problem of assuring a 100-year supply of groundwater for developments when, "ADWR's 'groundwater adequacy certificate' considers only availability for human use, not ecological considerations," a new bill was passed in the Arizona state legislature in 2007 (Kempthorne & Myers, 2008, p. 67). According to the Secretary of the Interior's report to Congress:

> This bill authorizes a county or municipality to adopt by unanimous vote an ordinance requiring an adequate water supply before any subdivision may be approved. This action, in conjunction with the establishment of the Upper San Pedro Water District, requires the director of the Arizona Department of Water Resources to adopt rules for water adequacy that are consistent with the sustainability goal of the District. (Kempthorne & Myers, 2008, p. 67)

These changes mean that water is now managed more comprehensively than ever along the San Pedro River.

However, despite the progress that has been made, challenges will continue to arise surrounding water use and management in Arizona over the coming decades. Climate predictions indicate that, "Demand for groundwater in arid and semi-arid regions of the world is expected to increase over time, not only in response to population pressures but also due to climate change. For the southwestern United States and subtropical regions worldwide, the Intergovernmental Panel on Climate Change (IPCC) projects a decrease in total precipitation as well as an increase in temperatures—both of which will add more stress to riparian systems" (Saliba & Jacobs, 2008).

Summary: Discussion and Conclusions

Management Suggestions

During the interview portion of this study, experts were asked to make suggestions for improving management of ground and surface water use conflicts in their states. One interviewee summed up the responses well by recommending a list of the necessary pieces to effective management: “Good sound science. Good studies. Good technical data. Good water law. Good administration.” These components were repeatedly recommended by experts from each of the states. Two other suggestions that were raised multiple times were improving storage of water supplies and promoting cooperation when rules need to be adjusted to changing circumstances.

Wyoming is quite different from many of its neighboring states in that it enjoys a small human population and many headwaters, especially in the western half of the state. While courts in Idaho and Colorado have been sorting through surface and groundwater disputes for years, the first such conflict ever to reach the courts in Wyoming is just now being addressed. Because of its unique position, Wyoming can look at the major problems and advantages of conjunctive management in neighboring states to and integrate the best parts of each to design the most effective system possible well before large-scale conflicts well up within these borders.

Good Sound Science/Studies/Technical Data

One interviewee in Idaho said, “On the technical side, more information can always be better. As we use the tools we can improve them and they can be better. Make sure the science is as good as possible. Good science helps on the administration side to answer delivery calls and helps decide where and how to improve the aquifer.”

These sentiments were repeated by another interviewee who said, “The lack of hydro-geologic evidence is the greatest barrier to effective management. This is related to science. How much does pumping of a well affect a stream and where, and therefore what should be outcome of curtailment?”

All three people interviewed about Wyoming commented on the need for good technical data. “The greatest barrier to effective management in this state is not knowing how hydrologic connectivity works.” Another interviewee asked, “The biggest issue is always the scientific issue. How do you tell what water starts in the ground and ends up at the surface, and how much, and how do you know where it’s moving?”

The only state where experts did not express a need for additional science was Washington. “Recently Washington had a big model [of the Yakima Aquifer] done by USGS so you can figure out if you are pumping in one place when and where and how it will affect the river. People are beginning to download the model and use it. … We have a lot of groundwater/surface water studies in Washington. Science has always been a component of our process here. There is not a shortage of science.”

Another interviewee, however, countered this by saying, “Until there’s been a study and models developed (which is very expensive) in every area of the state, it’s possible to guess wrong and over-appropriate water.”

Good Water Law

Interviewees from several states felt that their rules are on the right track, but need to be refined as they play out in the courts. An expert from Idaho said, "The greatest barrier is the lack of clarity in governing legal principles. … Each court decision clarifies the legal principles a bit more."

In Colorado, one person interviewed pointed out that the water law system, "was developed in such a way that there are now competing interests for a supply that was always limited." Now the system needs to be changed, but there is great resistance to changing any existing rules because someone gets hurt by it.

Even among some states that have incorporated groundwater into the prior appropriation system, two separate water codes still exist. In Washington, interviewees called for adoption of one unified water code. "In the one major general adjudication the court joined only surface water claimants and not groundwater claimants. Surface water claims are being adjudicated and can be regulated against but not groundwater claims."

Good Administration

Because water management involves competition among many users for a supply that spans a large area, careful oversight and regulation of the resource is absolutely necessary. Administration is closely linked to water law; once the laws have been created, administrators actually distribute the limited water supplies through curtailments and water calls and implementation of other rules. One interviewee in Idaho stressed the benefits of having effective administration by saying, "We've been blessed with a good director of IDWR in Idaho. The IDWR has taken a serious, even-handed approach to the question of how to integrate conjunctive management."

Balancing administrative approaches with all the other components of water management is also important. "When people make delivery calls there [has to be an] active administration to answer it. Some people focus just on management side. Well, that's important, but it doesn't eliminate need for administration during shortages and conflicts. The goal is to minimize the need for administration by better management and storage."

Improving storage

One interviewee from Idaho recommends addressing water conflicts by finding, "more storage and looking at additional supplies[.] … Each year 36 million acre feet flow out of Idaho in the Snake River and we only have capacity to store 8 million acre feet. Other basins can store 200-400% of their flows and we can only store 25%."

In Colorado, "the aquifer along the Front Range … is getting drawn down from development, and communities have to look for other sources of water to meet their municipal water needs." Ideas to create massive storage reservoirs in the mountains or even to pipe huge amounts of water from other watersheds have been explored as a solution to this problem.

Some states have law for artificial storage of groundwater by injecting good water into aquifers. "This law allows an entity or person to artificially store water underground and recover it later. This approach is much bigger in southwest (such as in Arizona), but it is relatively new here (Washington). We see it as a strategy that could work well."

Arizona has probably done the most of any state in this investigation with underground water storage. For example, subdivisions can only be built if they have an assured water supply for 100 years. "[T]he supply of water to the subdivision cannot be groundwater. You can use water that is transported from the Colorado River in canals or, if you can't take Colorado River water directly, you can pay a replenishment district to use Colorado River water to recharge groundwater supplies and then you can pump." Arizona's goal of achieving "safe yield" in all Active Management Areas by 2025 entails accounting for both natural inflows to aquifers and injecting water.

Cooperation and collaboration

One interviewee identified "the difficulties of communication and cooperation" as the greatest barrier to effective management of ground and surface water. "You can fight forever in the courtroom. It's harder to sit down and talk and come up with a solution that allows everyone to move forward. There have been some recent settlement frameworks that are monumental successes, but they require cooperation and setting aside preconceived ideas."

An interviewee in Washington pointed out the importance of, "convincing the public about connectivity because there is so much ignorance about how groundwater works. If the state sets an instream flow and says we're going to limit surface and groundwater to protect that flow, people get all up in arms. It takes a lot of effort to educate the public, especially when there is a lack of full understanding even by ourselves of groundwater."

In Wyoming the sentiment of one expert is that there is a preference, "to have water users work it out among themselves. Work collectively. … The water users are the ones who know the most about what is going on." Effective management of such a complex and valuable resource that is increasingly in short supply will take collaboration and input from many different stakeholders.

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See also:

Idaho
Idaho Constitution – Article XV, Water Rights
Idaho Administrative Procedures Act – Idaho Statutes, Title 67, Chapter 52

Washington
Washington Constitution – Article XXI, Water and Water Rights
Revised Code of Washington
Washington Administrative Code

Colorado
Colorado Constitution – Article XVI
Colorado Revised Statutes
Colorado Code of Regulations

Wyoming
Wyoming Constitution – Article VIII
Wyoming Statutes
Rivett v. Wyoming State Engineer (not yet decided, all documents retrieved from Wyoming 7th District Court, March 2009)

Arizona
Arizona Constitution – Article XVII
Arizona Revised Statutes – Title 45

2. Development of a Modeling Framework to test Conjunctive Management Strategies: Demonstration on the Bates Creek, Wyoming, Alluvial Aquifer

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ABSTRACT

A contemporary modeling framework based on the USGS *MODFLOW* and *GWM* programs is presented as a methodology for developing a conjunctive management strategy within the prior-appropriations water rights doctrine. An extensive review of the literature establishes the utility of the approach, and demonstrates the breadth and depth of work that has been performed on the conjunctive management problem. The modeling framework for conjunctive management is demonstrated.

Introduction

To address anticipated future conflicts between senior surface water rights and junior ground water rights, it is necessary to develop of a functional model to identify optimal conjunctive use strategies. This project combined a legal analysis with hydrologic modeling in order to assess the viability of a number of conjunctive use water management models for alluvial aquifer systems.

Four basic legal doctrines govern groundwater development: (1) the common law “rule of capture,” which allows unlimited withdrawal of water below owner’s land; (2) the American rule, more common in the Eastern states, which allows “reasonable use” reasonable and beneficial purposes; (3) correlative rights, in which landowners have right to proportionate share of water; and (4) the prior appropriation doctrine, which allows those who first put water to beneficial use to continue to do so (Bryner and Prucell, 2003).

Wyoming, like most states in the West, has a permit-based prior appropriation system. Wyoming law anticipates the potential for interconnectedness of surface and groundwater supplies and provides that, in such cases, surface and groundwater rights are to be correlated into a single schedule of priorities. (Wyo Rev. Statute § 41-3-916). Ground and surface supplies are not presumed connected unless proven otherwise (Tellman, 2003). In actual application, however, conjunctive management of surface and groundwater supplies in prior appropriation systems can be problematic. In Idaho, for example, conjunctive management rules for the Snake River basin were recently struck down for failing to conform to constitutionally mandated components of the prior appropriation doctrine.

Management tools developed in other states that address conjunctive water management were surveyed. The assessment of management options include a “no management” option in which prior appropriation allocations of groundwater continue without regard to potential impacts on other water rights within the hydrologic system. “Safe yield” strategies were given particular attention, including tools for addressing the increasing need to make predictive assessments of allowable use of junior rights based on surface water availability and demands by senior rights.

Effective conjunctive management of ground and surface water resources is essential where wells pump from valley-bottom alluvial aquifers that are in contact with surface waters. Pumping from alluvial aquifers can lower the local water table in alluvial aquifers near streams below the water level in the stream. This results in a vertical head gradient into the stream bed, and causes the stream to lose water to the alluvium, a process that is called “induced infiltration”.

Alluvial wells are not in intimate contact with the surface water. There are limits to water transfers from the surface water body or stream to the alluvium, attributed to streambed hydraulic conductivity, porosity and hydraulic conductivity of the alluvium, pumping rates, intercepted recharge, the distance from the well(s) to the stream (Ahlfeld 2004, Nadim et al. 2006), and fluvial geomorphology (Woessner, 2000).

Establishing a mechanism for effective conjunctive management requires 1) identification of potential operational management strategies; 2) development of a scientifically-sound means of justifying the action; 3) accurate description of all surface water and groundwater rights; and 4) identifying the magnitude of all relevant physical characteristics (model parameters) that describe the conjunctive system.

This report describes data needs, reports on similar past and ongoing efforts elsewhere in the Western U.S., and applies standard USGS methodologies on the Bates Creek irrigation district near Casper, Wyoming, as a demonstration of the approach using literature parameter values and assumed surface discharges and pumping rates. The purpose of this demonstration is not to provide a final management plan, rather it is to show how a management plan might be developed.

Review of Literature

The problem of management of conjoined surface and ground waters is vexing. Much work has been done on the problem, yet a single best methodology has not been developed to date. Since the 1970's numerical modeling approaches have been the predominant means of trying to determine the effect of groundwater pumping on stream flows. Today, the majority of studies involve the U.S. Geological Survey three-dimensional, finite difference MODFLOW (Harbaugh and others, 2000) groundwater simulator with a variety of add-on packages for simulating surface water flow and constraint-based optimization aimed at minimizing negative impacts.

Wilson and Anderson (2006) performed a literature review that identified a number of relevant published papers, which is presented in Table 1 in an updated form to inform the reader of the scope of work that has been published on modeling to address the subject of this report.

Table 1. Recent papers related to conjunctive ground- and surface-water management. Note: DSS stands for "Decision Support System". (Updated from Wilson and Anderson, 2006)

Region	Author(s),date	Subject
General	Ahlfeld, et al., 2005	GW management process for MODFLOW-2000
	Ahlfeld and Mulligan, 2000	Optimizing ground water systems; MODOFC
	Basagaoglu, 1999	Cost effectiveness of conjunctive use policies
	Belaineh et al., 1999	Linking reservoirs and stream/aquifer systems
	Jenkins, 1968	Rate/volume stream depletion by wells
	Marino, 2001	Regional water supply models
	McHugh, 2003	Determining permitting and compliance rules
	Onta et al., 1991	3-step model: interactions, alternatives, costs
	Philbrick and Kitanidis, 1998	Surface/subsurface capabilities
	Ratkovich, 1998	Water deficiencies
	Schmidt et al., 2003, 2006	New FARM package for MODFLOW
	Silka and Kretschek, 1983	Incorporating climate into GW simulations
	Wagner, 1995	Simulation-optimization GW management methods
	Young, 2005	Non-market economic valuation methods
	Zhang et al., 1990	Modeling stream/aquifer systems
	NRC, 2000	Groundwater Management at Regional and National Scales
Australia	Chiew et al., 1995	Cost effectiveness of conjunctive use policies
Argentina	Correa, 1990	Short-term optimization (1 yr) model
	Menenti et al., 1992	Agricultural optimization model
Arkansas	Peralta and Peralta, 1986	Regional, sustained-yield model
	Peralta et al., 1990	Optimal management of conjoined waters
California	Andrews et al., 1992	Simulating surface water distribution; KCOM
	Bergfeld, L. G.	Investigative study of conjunctive use opportunities
	Dvorak, 2000	Operating rule effects on yield
	Fleckenstein et al. 2006	MODFLOW low-flow management
	Jenkins et al., 2004	Economic-engineering optimization model
	Knapp and Olson, 1995	Ground/surface and recharge model
	Matsukawa et al., 1992	Management model, Mad River Basin
	Pulido-Velazquez et al., 2004	Potential and limitations
Colorado	Fredericks et al., 1998	DSS based on MODSIM
	Morel-Seytoux, 2001	Model evaluates augmentation plan
	Restrepo and Morel-Seytoux, 1989	Calibration study with SAMSON
Connecticut	Nadim et al. 2007	MODFLOW instream flow, fisheries maintenance
England	Seymour, et al., 1998	GW recharge, flow and surface interaction

Florida	Yan and Smith, 1994	SFWMM + MODFLOW simulation
Idaho	Cosgrove and Johnson, 2004	Quantification of impacts to surface water
	Miller et al., 2003	Snake River Basin model expansion
	Shannon et al., 2000	GIS and basin flow modeling
Nebraska	Cannia et al., 2002	Hydrostratigraphic units for COHYST
	Carney et al., 2002	Stream depletion and COHYST
	Henszey et al., 2002	Water levels versus grass response curves
	Krapu, 2002	Sandhill crane needs and the Platte River
	Kress et al., 2002	Surface lithology profiling
	Kress, et al., 2004	Use of continuous seismic profiling
	Landon et al., 2002	Riparian woodland evapotranspiration
	Lewis and Woodward, 2002	Describing COHYST
	Peterson et al., 2002	COHYST construction, calibration
	Rus et al., 2002	COHYST and streambed conductivity
	Stansbury et al., 1991	DSS for water transfer evaluation
Rhode Island	Barlow et al., 2003	Stream/aquifer model for minimum streamflow effects
	Barlow and Dickerman, 2001	As above, but in a USGS paper
Spain	Pulido-Velazquez, et al., 2006	Economic optimization of conjunctive use
Texas	Watkins and McKinney, 1999	Alternative screening model
Washington	Scott et al., 2004	Forecasting climate variability
Wyoming	Glover, 1983	Conjunctive management modeling

Similar Efforts Elsewhere

Colorado

In 2003, the Colorado legislature recognized the importance of planning for long-term water needs. In that year, the legislature authorized the Colorado Water Conservation Board (CWCB) to initiate a Statewide Water Supply Initiative (SWSI), with the overarching objective of maintaining an adequate water supply for the State. As part of this effort, development started on River Decision Support Systems (RDSS), which were planned for each major drainage basin. The resulting product is called the Colorado Decision Support Systems (CDSSs). The major goals of the CDSSs are to:

- Develop accurate, user-friendly databases that are helpful in the administration and allocation of waters of the State of Colorado,
- Provide data, tools and models to evaluate alternative water administration strategies, which can maximize utilization of available resources in all types of hydrologic conditions,
- Be a functional system that can be used by decision makers and other and be maintained and upgraded by the State, and,

- Promote information sharing among government agencies and water users.

This effort has been funded at approximately $500,000 per year since 2003. Support for the RDSS by the Colorado legislature in FY08-09 was $535,000. In FY 09-10 funding for the RDSS was $453,000 to the Colorado Water Conservation Board plus another $205,400 to the Water Resources Division, which funds 6 FTE staff. The CDSS effort is most advanced on the South Platte river, where the effort is aimed at setting up a single-layer *MODFLOW* model of the alluvial aquifer. The model active area is approximately 2500 square miles, and the model uses a 1,000 ft. grid size, and monthly stress periods. The CDSS has an external peer-review panel which meets regularly to evaluate progress, engage the advice of experts, and plan future developments. As of the last report in 2009, the CDSS is being calibrated in the South Platte alluvial aquifer.

Nebraska

The States of Wyoming, Colorado, Nebraska, and the U.S. Fish and Wildlife Service and Bureau of Reclamation, entered into an agreement which is called the Platte River Cooperative Agreement in 1997 to address minimum in-stream flows to maintain aquatic habitat for endangered species in the central Platte River in Nebraska. Part of this agreement requires no new depletions of Platte River flows or flows to tributary streams. As part of this cooperative agreement, a Cooperative Hydrology Study (COHYST) is underway, which aims to create scientifically supportable data sets and modeling capabilities to address the problem. To date, well over $1 million has been spent on this study. In February, 2010, COHYST received a grant of $500,000 to combine the Conjunctive Management Study and COHYST data bases.

MODFLOW

The USGS groundwater simulation code MODFLOW (Harbaugh et al., 2000, McDonald and Harbaugh, 1988) is widely used to analyze groundwater flows in the United States and abroad. *MODFLOW* can describe the three-dimensional variation of aquifer properties using a finite-difference discretization. The formulation of *MODFLOW* is modular allowing the addition of process modules as the situation requires. These add-on process modules include simulation capabilities for lakes, streams, and land-surface recharge, among others. The stream packages *STR*, *SFR*, and *SFR2* (Prudic, 1989; Prudic et al., 2004; Niswonger and Prudic, 2005) were developed to improve the ability of *MODFLOW* to simulate conjoined surface and ground waters. The most recent stream routing module *SFR2* includes unsaturated flow beneath streams that are above the water table. All three of these stream routing modules treat surface flows as steady. Exchanges of water from the stream to the aquifer is assumed to be controlled by a stream bed layer of known thickness and hydraulic conductivity.

The USGS had developed more sophisticated streamflow modeling approaches that can be used to simulate unsteady flows. These include *DAFLOW* (Jobson and Harbaugh, 1999) and *MODBRANCH* (Schaffrenek, 1987). The *DAFLOW* scheme solves the 1-D diffusive-wave form of the de St. Venant equation of motion, while *MODBRANCH* uses a 4-point implicit solution of the full-dynamic form of the de St. Venant equations. Both of these schemes use an iterative approach to calculate the coupled changes in groundwater head and surface water depth over a time step.

The *DAFLOW* scheme was developed to simulate unsteady flows in low-order streams, and

Jobson and Harbaugh (1999) report that the accuracy of the method is higher in steeper streams. The full dynamic-wave representation used in *MODBRANCH* in theory should be more accurate in all streams, however the four-point implicit solution has known deficiencies in situations where flow is transcritical as can often occur in steep reaches or at significant channel constrictions such as bridge openings (Meselhe and Holly, 1997).

Given that high-temporal resolution surface flow data do not exist in Bates, Corral, and Stinking creeks, the unsteady flow simulation capabilities offered by the *DAFLOW* and *MODBRANCH* models are not needed. We opted therefore to use the SFR2 stream flow routing package in MODFLOW simulations of the Bates creek study area because it has the level of sophistication required to simulate the salient surface-water flow features required in this study, particularly surface water diversions, which are not part of the *STR* and *SFR* packages. The SFR2 package also includes unsaturated zone flow beneath streams (Niswonger et al, 2006). The use of the SFR2 package, however, required use of the 2005 version of *MODFLOW* (Harbaugh, 2005) which is a difference from our original proposal, which called for the use of the 2000 version of *MODFLOW*.

***MODFLOW* Interface Selection**

This project aims to recommend a numerical modeling framework for use by the Wyoming State Engineer's office. As such, creation of data sets for a model such as MODFLOW requires the use of an interface to process geo-spatial data and produce model inputs. There are a number of options for this task, we considered two different options, which are discussed below.

The first *MODFLOW* interface considered is called Argus ONE (Argus ONE Ltd., 2010). The actual *MODFLOW* graphical user interface (GUI) is available at no cost from the USGS, but before it can be used, the user must purchase the Argus ONE GIS and Grid modules, which cost $1000 at the time of writing. Furthermore, Argus ONE is a GIS system with its' own data structures and learning requirements. Given the prevalence and widespread acceptance of the *ARC/INFO* Geographic Information System, the Argus ONE requirement that users learn a new GIS software package just to run *MODFLOW* was seen as a major drawback.

The Groundwater Modeling System (*GMS*) interface for *MODFLOW* (Aquaveo LLC, 2010) is a full *MODFLOW* GUI that also serves as an intermediary between *ARC/INFO* and *MODFLOW*. The *GMS* software is more expensive than the Argus ONE GIS package, with a cost of $4,450 at the time this report was written for the standard *MODFLOW* package which includes *MODPATH* particle tracking, and the (Parameter ESTimation (*PEST)* automatic model calibration tool. Given that the *GMS* serves as an intermediary package that allows *ARC/INFO* geospatial data to be used directly in *MODFLOW* setup, this capability justifies the additional cost above the cost of the Argus ONE GIS software.

The *GMS* software supports its' own customized version of *MODFLOW* that was derived from *MODFLOW* 2000. The primary customization in the GMS version of *MODFLOW* is the use of the HDF binary data storage standard, which is not used by the USGS version. The HDF data storage standard is widely used but not by the USGS. GMS can be used to create input data sets for *MODFLOW* 2005, as it has the option of writing ASCII input files that *MODFLOW* 2005 will read. Only minor text editing is required by the user before running the stock USGS *MODFLOW* 2005 code with input data written by the GMS software package.

***MODFLOW* Stability Issues**

During a MODFLOW simulation, it is not unusual for one or more model grid cells to go dry, which means the water table is drained to the aquifer bottom. To continue the simulation, the MODFLOW code will remove a cell that becomes dry from the computational domain. MODFLOW does allow dry cells to re-wet, but the solution can become unstable. A number of different efforts to improve stability of MODFLOW during cell-rewetting have been developed (Doherty, 2001; Painter et al., 2008), but to date these techniques have not been incorporated in the main USGS code.

Another factor that can cause dry cells and affect the stability of a *MODFLOW* simulation occurs if a well is pumped at a rate that is higher than the aquifer can supply water to that well. There may be wells in the study area that can actually pump water at a rate faster than the aquifer can fill the cone of depression, and the cone of depression will reach the screen or pump elevation. In the model this creates a dry cell, and if this occurs, the user will have to break the simulation into smaller stress periods and turn the well off in the model before this condition occurs.

***Ground Water Management (GWM)* Optimization Code**

Since the 1960s, numerical ground-water flow models have become increasingly important tools for the analysis of ground-water systems. More recently, ground-water flow models have been combined with optimization techniques to determine water-resource management strategies that best meet a particular set of management objectives and constraints.

Optimization techniques are a set of mathematical programs that seek to find the optimal (or best) allocation of resources to competing uses. In the context of ground-water management, the resources are typically the ground- and surface-water resources of a basin and (or) the financial resources of the communities that depend on the water. The management objectives and constraints are stated (or formulated) mathematically in an optimization (management) model. Combined ground-water flow and optimization models have been applied to various ground-water management problems, including the control of water-level declines and land subsidence that could result from ground-water withdrawals, conjunctive management of ground-water and surface-water systems, capture and containment of contaminant plumes, and seawater intrusion. Detailed guides to the underlying theory and application of management models can be found in textbooks by Willis and Yeh (1987), Gorelick and others (1993), and Ahlfeld and Mulligan (2000), and to literature reviews by Gorelick (1983), Yeh (1992), Ahlfeld and Heidari (1994), and Wagner (1995).

GWM (Ahlfeld et al., 2005 and 2009) is a Ground-Water Management process module for the U.S. Geological Survey modular three-dimensional ground-water model, *MODFLOW*-2000 (Harbaugh and others, 2000) and *MODFLOW*-2005 (Harbaugh, 2005). GWM uses a response-matrix approach to solve several types of linear, nonlinear, and mixed-binary linear ground-water management formulations. Each management formulation consists of a set of decision variables, an objective function, and a set of constraints.

Three types of decision variables are supported by GWM: flow-rate decision variables, which are withdrawal or injection rates at well sites; external decision variables, which are sources or sinks of water that are external to the flow model and do not directly affect the state variables of the simulated ground-water system (heads, streamflows, and so forth); and binary variables, which have values of 0 or 1 and are used to define the status of flow-rate or external decision variables. Flow-rate decision variables can represent wells that extend over one or more model cells and be active during one or more model stress periods; external variables also can be active during one or more stress periods.

A single objective function is supported by *GWM*, which can be specified to either minimize or maximize the weighted sum of the three types of decision variables. Four types of constraints can be specified in a *GWM* formulation: upper and lower bounds on the flow-rate and external decision variables; linear summations of the three types of decision variables; hydraulic-head based constraints, including drawdowns, head differences, and head gradients; and streamflow and streamflow-depletion constraints.

The Response Matrix Solution (RMS) Package of GWM uses the Ground-Water Flow Process of MODFLOW to calculate the change in head or streamflow at each constraint location that results from a perturbation of a flow-rate variable; these changes are used to calculate the response coefficients. For linear management formulations, the resulting matrix of response coefficients is then combined with other components of the linear management formulation to form a complete linear formulation; the formulation is then solved by use of the simplex algorithm, which is incorporated into the RMS Package. Nonlinear formulations arise for simulated conditions that include water-table (unconfined) aquifers or head-dependent boundary conditions (such as streams, drains, or evapotranspiration from the water table). Nonlinear formulations are solved by sequential linear programming; that is, repeated linearization of the nonlinear features of the management problem. In this approach, response coefficients are recalculated for each iteration of the solution process. Mixed-binary linear (or mildly nonlinear) formulations are solved by use of the branch and bound algorithm, which is also incorporated into the RMS Package.

Four types of constraints can be specified in a *GWM* formulation: upper and lower bounds on the flow-rate and external decision variables; linear summations of the three types of decision variables; hydraulic-head based constraints, including drawdowns, head differences, and head gradients; and stream flow and stream flow-depletion constraints. Two types of streamflow constraints are allowed—constraints on the upper and lower bounds on streamflow and constraints on the upper and lower bounds on streamflow depletion.

GWM allows for the simultaneous use of both managed and unmanaged wells at model cells. For example, the user might specify an unmanaged withdrawal rate (that is, a background stress) of 1.0 ft3/s at a particular cell with the WEL Package; the user also could define a managed withdrawal at the same cell by use of a flow-rate decision variable in *GWM*. The total withdrawal rate at the cell at the end of the *GWM* run would then equal the sum of the unmanaged withdrawal rate (1.0 ft3/s) and the managed withdrawal rate determined by *GWM* for the decision variable.

Output from *GWM* includes response coefficients, which represent the partial derivative of the state variable of interest (e.g. stream flow at a point) with respect to a particular stress or well pumping rate. Response coefficients are approximated using a first-order, finite-difference perturbation method. The precision of the response coefficients is an indication of their ability to reflect the actual response of the calculated system state to changes in stress. Values of head are iteratively generated until the maximum calculated change in head at any model cell is less than a specified convergence criterion between iterations. The precision of the resulting heads can be estimated to be of the same magnitude as the convergence criterion. As a result, the precision of the response coefficients depends upon the convergence criterion used by the flow process.

One significant benefit of using the *GWM* package is that response coefficients are calculate for each stress period. This information can be used to track changes in the effect of different stresses on different constraints (e.g. well pumping on stream flow) over time. Temporal changes in stress coefficients indicate lags in time. These can be interpreted as system "memory" as well. GWM results can indicate, for instance, that a well far from the stream may have a more significant effect on stream flow some time after the start of the irrigation season compared to a well that is nearer the stream.

Data Needs

The following data are needed to simulate the hydrogeology of the study area using *MODFLOW*:

- Bedrock surface elevations
- Land surface elevations
- Stream locations
- Lateral boundary conditions (constant head, constant flux, no-flow)
- Lower boundary conditions (flux to/from bedrock aquifer)
- Stream bed impeding layer thickness
- Stream bed impeding layer saturated hydraulic conductivity

The following data are required to develop MODFLOW stress period input data:

- Irrigation-based recharge quantities
- Irrigation Recharge areas
- Canal seepage
- Area-wide recharge from rainfall and snow melt
- Actual irrigation pumping rates and schedules
- Actual residential pumping rates
- Evapotranspiration from irrigated fields
- Evaporation from streams and bare soils
- Measured streamflow diversions and schedules
- Stream flow hydrographs at model boundaries

Calibration requires spatially-varied aquifer head data. Actual data requirements depend on the particular situation, seasonality, unsteady stresses, meteorological forcing, etc. An imperative need is that the data collection be continuous and period span sufficient time to capture seasonality and the effects of climate variability. This requires data collection over a several year period, at a minimum.

Bates Creek Study Site

The problem of conjunctive management in Wyoming is unique. Compared to the large river-valley irrigation projects along the North Platte and Platte Rivers in Nebraska, and the South Platte and Arkansas Rivers in Colorado, irrigation areas in Wyoming where conjunctive management issues have arisen tend to be along smaller rivers and creeks. This project did not contain a field data collection component. Therefore, we relied upon data collected by others from a Wyoming irrigation district.

One such irrigation district in Wyoming is along Bates Creek before it joins the North Platte River. We obtained data on permitted wells and surface water diversions in the Bates Creek study area from the Wyoming State Engineer's office, and from the study by Glover (1983). The study area is located about 20 miles southwest of Casper, Wyoming. Bates Creek is a tributary to the North Platte River. Two significant drainages join Bates Creek at the upper end of the study area, Stinking Creek and Corrall Creek. The study area is shown in Figure 16.

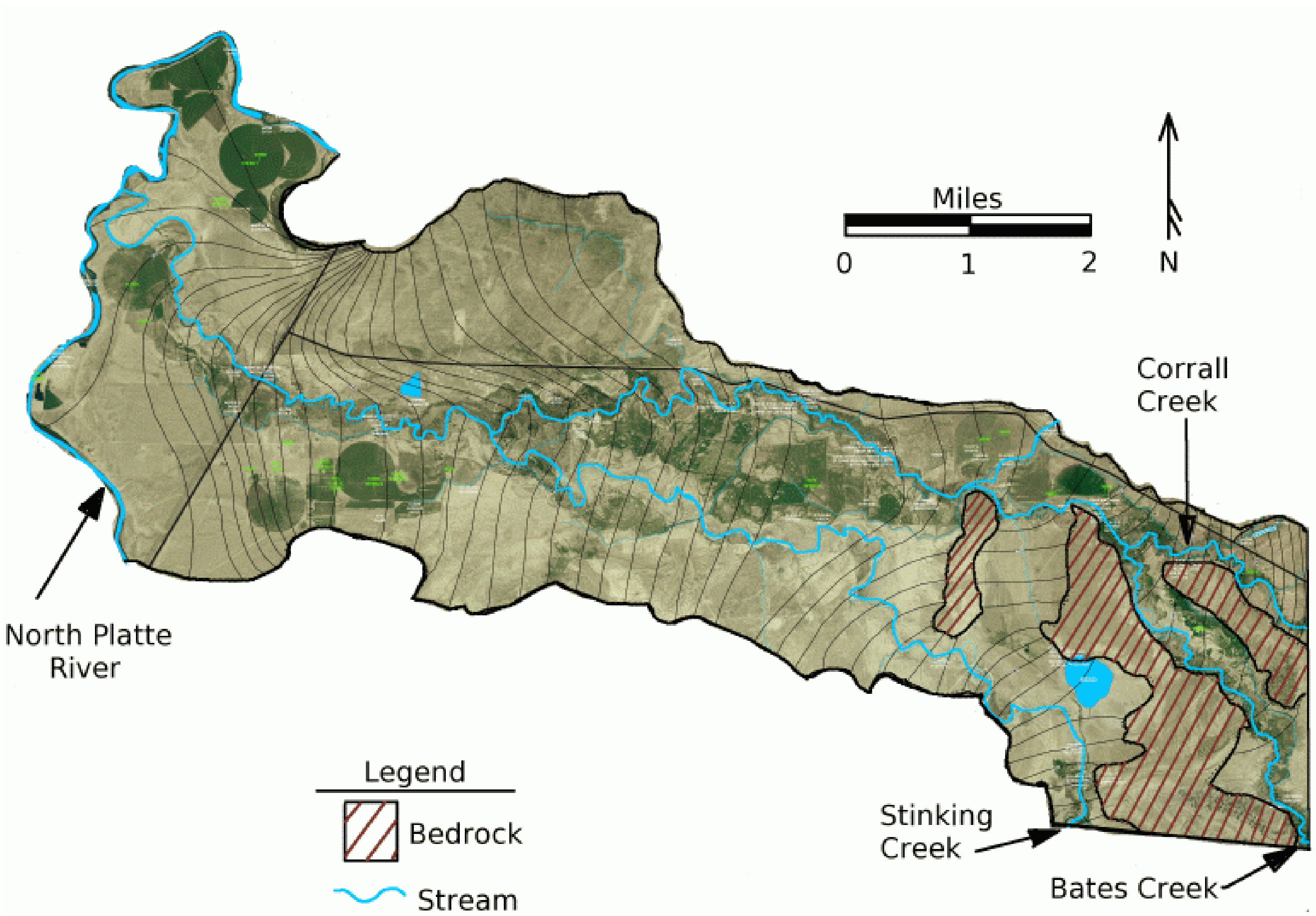

Figure 16: Bates Creek Irrigation District Study Area. The study area is bounded by the North Platte river on the western edge.

Past Studies of the Bates Creek Study Area

A comprehensive field investigation of the Bates Creek study site has not been performed at the time of writing of this report. Therefore, the quantity of data on aquifer properties and surface hydrology is limited. The lack of detailed surface hydrology data, known quantities of surface diversions and groundwater pumping prevent development of an actual conjunctive management plan for this area. Creation of such a plan will require more data than presently exist.

Glover (1983) developed a single-layer (depth-averaged) digital model of the Bates Creek alluvial aquifer using a computer code that is a precursor of the USGS Modflow software. Hydrologic data collected during 1977 and 1978 were used in model calibration. After calibration, the model was run under steady-state and transient conditions for three different scenarios. These scenarios included (1) no ground water pumping, (2) pumping by all existing wells, and (3) pumping by all existing and proposed wells. Simulations used average values of stream discharge, water use, and pumping rates. The simulation results indicated that the quantity of groundwater exfiltration to Bates Creek would decrease throughout the simulated period, which extended until 1988. The numerical study by Glover (1988) did not seek to identify the effect of individual wells on flows in Bates Creek within the context of prior-appropriation water rights doctrine.

Glover (1983) did not perform aquifer tests as part of his study. Rather, he used values of the saturated hydraulic conductivity (K) estimated from borehole samples to be in the range of 190 to 900 ft/day. Glover (1983) reported that the saturated thickness in the alluvial aquifer varies from 0 to more than 80 feet. Glover (1983) assumed that the specific yield (S_y) of the aquifer is 0.23, which is the same value found by Crist (1975) in the with the North Platte valley-fill aquifer in Wyoming. Glover (1983) reported that stream bed hydraulic conductivities at two locations were 1.65×10^{-5} ft/s and 2.43×10^{-5} ft/s. In his modeling study, Glover (1983) used a value equal to the average of these two values, 2×10^{-5} ft/s, and assumed that the thickness of the streambed impeding layer was 1 ft.

The digital aquifer simulation code used by Glover (1983) had a minimum grid size of 750 ft, a maximum grid size near the north and south model boundaries of 1,500 ft., and was calibrated against observed water levels. This calibration resulted in identification of saturated hydraulic conductivities on a grid-by-grid basis. Glover (1983) reported a root-mean-squared difference between measured and modeled ground water heads of 2.4 ft. The calibrated saturated hydraulic conductivity field is lost. Glover (1983) reported that his calibrated model was insensitive to variations in the specific yield parameters in the range of 0.20 to 0.25.

In transient simulations, Glover (1983) reported that groundwater depletions were not completely re-filled during the non-irrigation season. This result indicated that there is a “memory” in the system that is longer than one-year. As such, streamflow depletions will continue to increase over time due to the effect of pumping wells.

The primary limitations on the study reported by Glover (1983) are uncertainties in stream inflow and diversion rates. Average values of these inputs were used over the 10-year prediction period from 1979-1988. Because of this, there is considerable uncertainty in the meaningfulness of the numerical model results. The study by Glover (1983) did not consider the impact of pumping of individual wells.

Langstaff (2006) applied the analytical Glover-Balmer technique (Glover and Balmer, 1954; Jenkins, 1968) to investigate the effect of pumping of individual wells on stream flow depletions. Langstaff relied upon the parameters published in the Glover (1983) report. Results of this analytical methodology show how the irrigation wells in the Bates Creek alluvial aquifer have an effect on surface flows, the significance of this effect varies with pumping rate and distance from the creek. As expected, the effect is largest for wells that are pumping more water from the aquifer, and for those wells that are closest to the creek. The analytical method also shows that due to the "lag effect of distance" wells that are far from the creek can increase surface depletions weeks to months after those wells are turned off.

Langstaff (2006) writes that the results of his analytical study cannot be relied upon in detail. While Langstaff (2006) does not give detailed reasons for this statement, it is clear that the analytical methodology does not fully consider recharge from precipitation and irrigation, nor the interaction between wells.

Modeling Framework

The modeling framework we developed uses the USGS *MODFLOW* model for groundwater simulations and the Ground Water Management (*GWM*) optimization software to address management questions. Setting up the modeling framework requires the following steps:

1) Study area delineation and discretization

2) Locating available input hydrologic, ground water, diversions, pumping, land surface, channel, and climate forcing data

3) Development of *MODFLOW* steady-state stress period input files

4) Steady-State *MODFLOW* calibration using PEST against groundwater monitoring well data to estimate the aquifer hydraulic conductivity field

5) Development of *MODFLOW* unsteady stress period input files (based on meteorological and flow data, and observations of variable diversions and pumping rates)

6) Run transient simulations within *GWM* simulator to evaluate the sensitivity of streamflow discharges at diversion points to different time-series combinations of well pumping

7) Interpretation of results

Fig. 17 shows a flow-chart of the modeling framework that would be used to develop a management plan. There is no established methodology for developing the test scenarios in the context of prior-appropriation water rights. In this case we developed a method based on available surface flows as discussed in a later section.

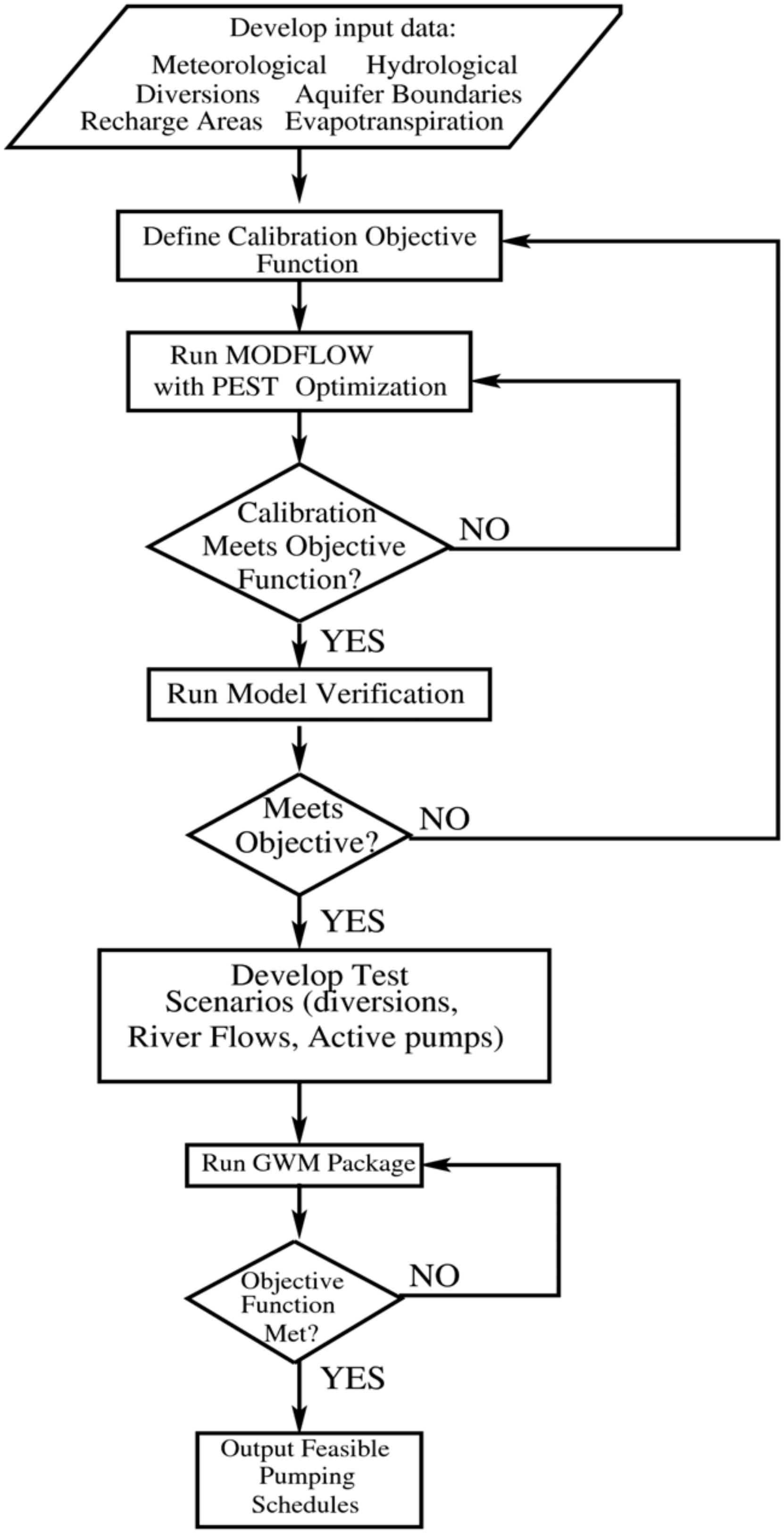

Figure 17: Modeling framework flow chart.

Groundwater wells are used in the Bates Creek study area for irrigation. Fig. 18 shows the location of the wells considered in this study. The wells are labeled Q1 through Q16, and their location coordinates and permitted pumping rates are listed in Table 2. Irrigation recharge areas are shown as green polygons. Headgates for surface water diversions are labeled G1 through G6.

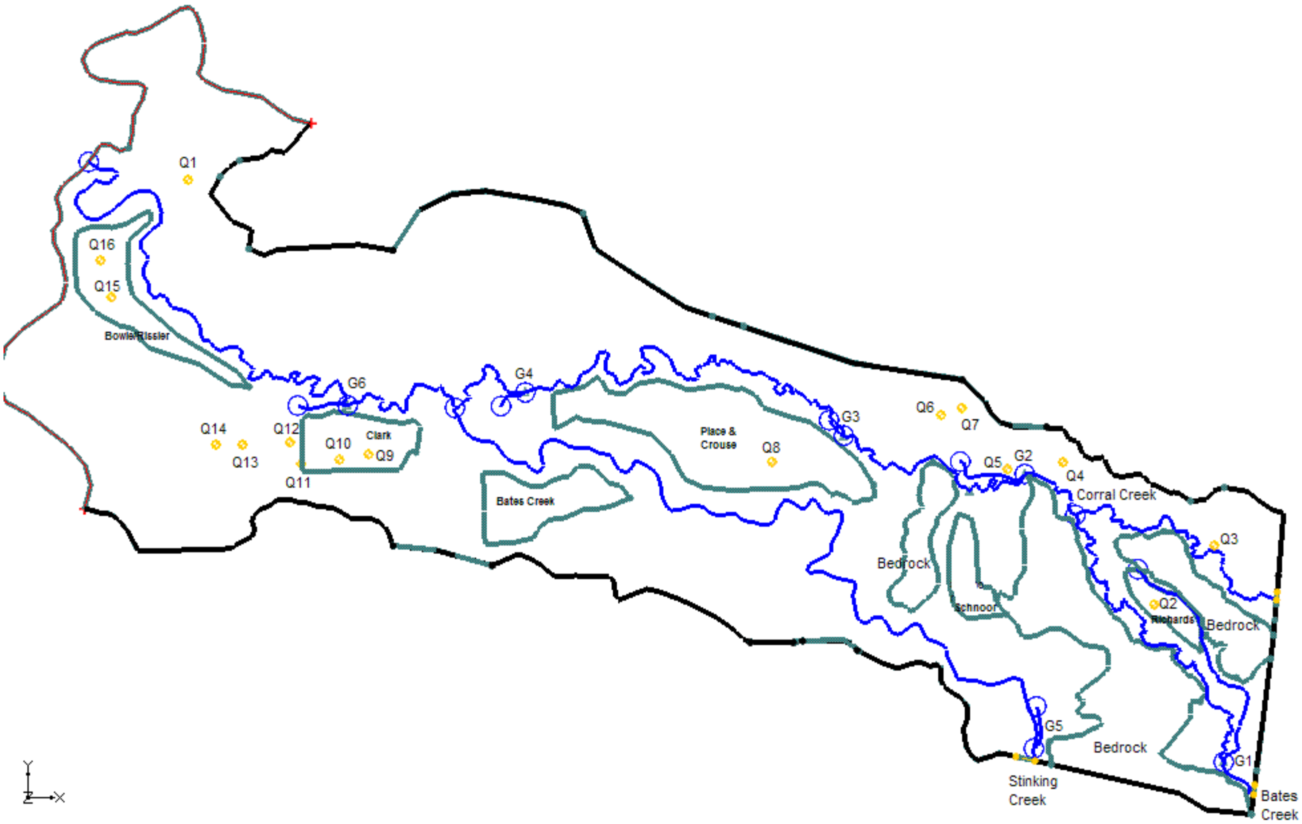

Figure 18: Location of wells and irrigation recharge areas within the study area.

Table 2. Permitted Wells in the Study Area

Permit No.	Well No.	Permitted Discharge (gpm)	row	column	Easting	Northing
62305	Q1	375	33	31	1509642	1127005
26060	Q2	950	84	123	1553418	1108037
28878	Q3	925	77	129	1556141	1110693
38044	Q4	1300	67	114	1549283	1114389
3622	Q5	875	68	109	1546779	1114071
38042	Q6	1100	62	103	1543778	1116507
38043	Q7	650	61	105	1544707	1116824
3995	Q8	1175	66	86	1536094	1114425

10364	Q9	1200	64	47	1517583	1114712
10365	Q10	1550	65	45	1516507	1114496
402	Q11	700	65	41	1514780	1114310
83022	Q12	150	63	40	1514253	1115271
111934	Q13	1550	63	35	1512113	1115178
111933	Q14	650	63	33	1510899	1115186
111471	Q15	500	46	23	1506161	1121760
111472	Q16	425	42	22	1505674	1123424

***MODFLOW* Steady State Calibration**

Data from Glover (1983) were used to calibrate the *MODFLOW* model. The PEST parameter estimation scheme (Doherty 2003) within *GMS* was used with pilot points to estimate the saturated hydraulic conductivity field. Results of the calibration at monitoring points are shown in Fig. 19.

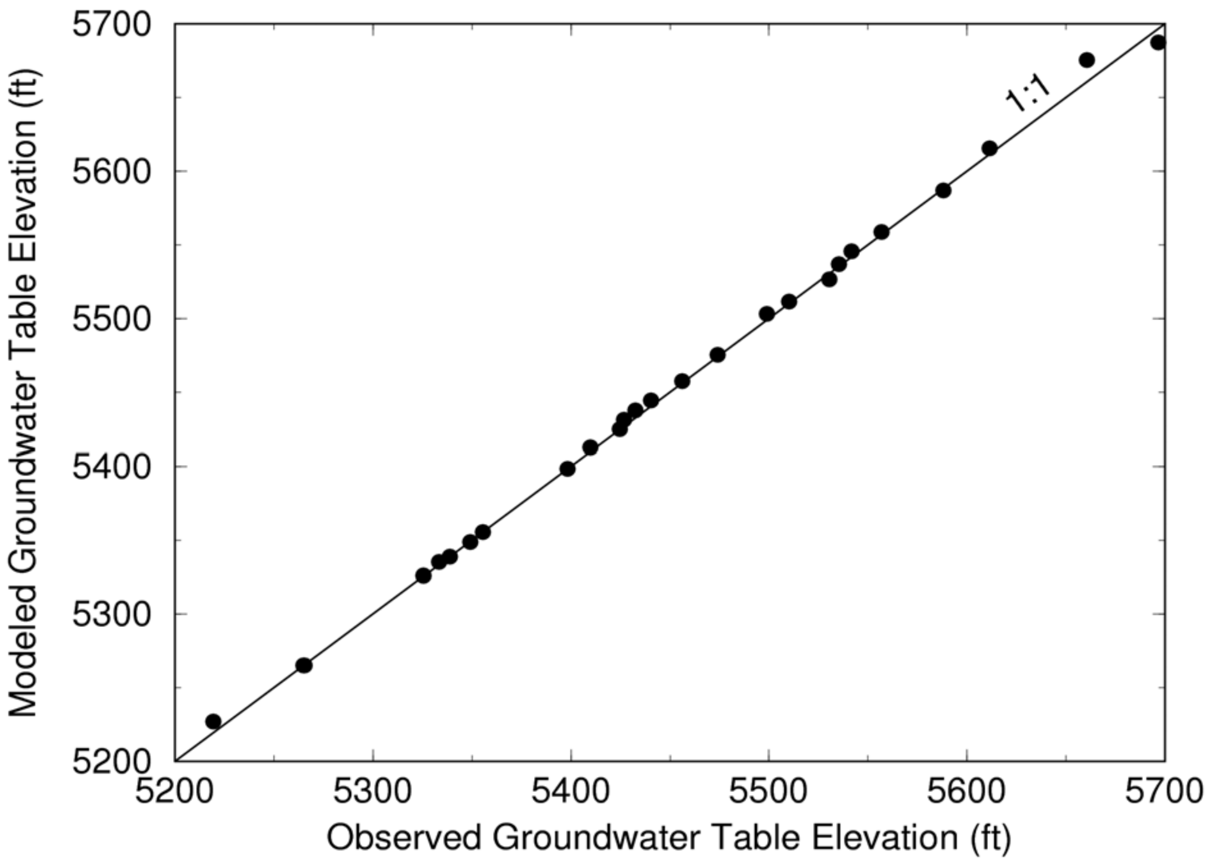

Figure 19: Agreement between observed and calibrated steady-state water table elevations, using data from Glover (1983).

Calibrated groundwater heads are shown in Fig. 20 with error bars shown at the locations of well data used in calculating the calibration objective function. Note that only two wells have significant deviations, both in the far north-east corner of the active domain. These two wells are in a region of steep groundwater table gradient. These wells are quite close together, with opposite sign on the error, indicating some local deviations in aquifer properties not captured by the *MODFLOW* model. The root mean square error of the calibrated heads, excluding the two wells in the north-east corner of the domain is 2.46 ft.

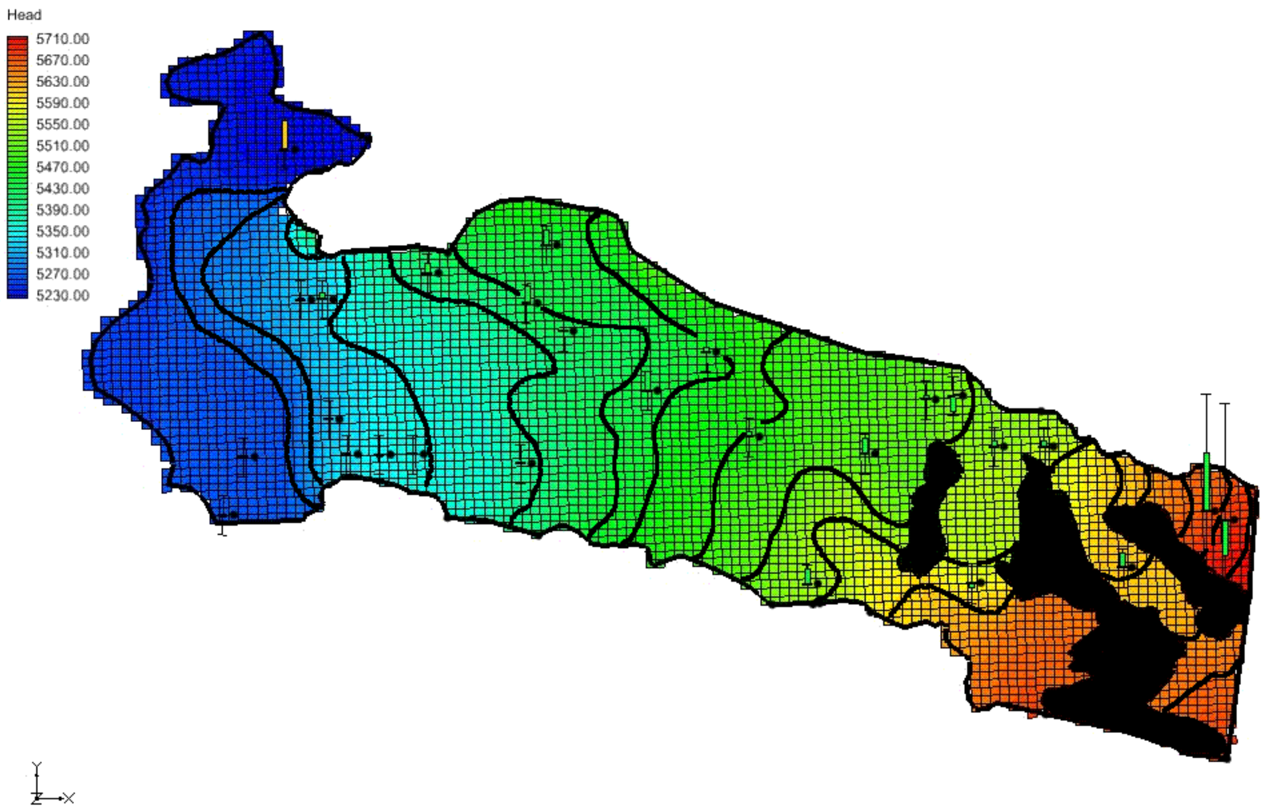

Figure 20: Calibrated steady state phreatic surface in study area. Black areas are bedrock. Error bars show calibration efficiency at monitoring wells using data from Glover (1983).

<u>Test Scenarios</u>

The prior-appropriations water rights doctrine imposes a set of constraints that are not typical for many groundwater pumping optimization scenarios outside of the Western U.S. The overall objective of the optimization is to maximize groundwater pumping while minimizing streamflow depletions as to not impact senior surface water rights. The class of senior water rights also have their own priorities that must be respected. In this demonstration, we considered the surface water rights listed in Table 3 obtained from the Wyoming Water Resources Data System on-line map server (http://ims2.wrds.uwyo.edu/Website/Statewide/viewer.htm, accessed Dec. 8, 2009). The quantities of water associated with each diversion were estimated, and are used in this demonstration as examples. The values listed in Table 3 <u>do not</u> represent actual diversion amounts approved by the water commissioner, and are used here for model framework testing only. It is up to the State water management agency to determine the appropriate amounts for each diversion. This list is also not exhaustive, but it contains most of the major surface water diversions in the study area.

Table 3. Assumed irrigation diversions at six major canal headgates in study area.

Div. No.	Ditch	Permit Date	Priority	Est. acre-feet per year	Maximum diversion during irrigation season (cfs)	*MODFLOW* input cubic feet per day
1	Richards Ditch	05/01/1888	3	1530	4.19	362,211
2	Place & Crouse Ditch	5/30/1896	4	1060	2.9	250,943
3	Bates Creek Ditch	03/14/1886	1	4500	12.33	1,065,326
4	Clark Ditch	06/18/1896	5	1490	4.08	352,741
5	Schnoor Ditch	05/15/1908	6	467	1.28	110,557
6	Bowie and Rissler Ditch	09/08/1886	2	2840	28,672	672,339

It is <u>very important</u> that the reader of this report understand that the surface diversions listed in Table 3 were used in this demonstration of the modeling framework as an example and are not actual values. In reality, the surface water rights in the Bates Creek area are more complex due to modifications to some diversions over time, and distinctions in the data base that require more detailed understanding of their meaning than the on-line database provides. The actual diversions allowed by the water commissioner should be used in the actual application of this modeling framework.

In developing our test cases, we decided upon six scenarios. These scenarios depend on whether or not there is sufficient flow in Bates Creek where it enters the model domain to support all six surface water diversions, or the most senior 5, 4, 3, 2, or 1 surface water rights. Our motivation in using these scenarios is unique to prior appropriations water rights doctrine. For instance, if there is only sufficient water in Bates Creek to support the most senior water right in the study area, the Bates Creek ditch, then it is impossible that groundwater pumping would impair the other five un-satisfied surface water rights as determined by surface measurements. This creates a conundrum for the water manager, as it raises the issue "Should junior ground water wells be allowed to pump while senior surface water rights are unmet?" The test cases used in this demonstration are listed in Table 4. Because we were lacking hydrologic data in Stinking and Corral Creeks, flows were assumed and held fixed at 1.27 and 3.10 cfs, (110560 cfd and 267840 cfd), respectively.

Table 4. Flow rates used in demonstration scenarios.

Scenario	Headgate Diversions (cfs) Number corresponding to Diversion No. in Table 3.						Bates Creek Inflow (cfs)
	1	2	3	4	5	6	
1	4.19	2.9	12.33	4.08	1.28	7.78	19.21
2	4.19	2.9	12.33	4.08	-	7.78	17.95
3	4.19	2.9	12.33	-	-	7.78	12.95
4	4.19	-	12.33	-	-	7.78	11.23
5	-	-	12.33	-	-	7.78	7.84
6	-	-	12.33	-	-	-	7.14

***MODFLOW* Stress Periods**

The *MODFLOW* simulation consisted of six stress periods spanning 11 months. The first stress period persisted for 182 days during the non-growing season, and represented a steady-state solution. The remaining five stress periods, each represented one month, for the months of May through September, and representing the growing-season. In the case where all surface water diversion rights were met during the entire growing season, the following flows were assumed in Bates Creek during the six stress periods:

Table 5. Assumed Bates Creek flows during different stress periods to insure that all assumed surface diversions were met without ground water pumping in Scenario 1.

Stress Periods	Bates Creek Flow (cfs)	Bates Creek Flow (cfd)
1	13.8	1,592,000
2	13.8	1,592,000
3	19.53	1,687,000
4 through 6	19.21	1,660,000

In this demonstration 70% of irrigation diversions were placed uniformly on the fields irrigated by each ditch as groundwater recharge. The fields are denoted by polygons and shown in Fig. 3. This assumes that 30% of the irrigation water applied in flood irrigation is consumed by evapotranspiration. We did not perform a detailed analysis of this percentage, as site-specific values will be needed.

Application of *GWM*

For the Bates Creek study, *GWM* imposes constraints on streamflow, as simulated using the SFR package (Prudic and other, 2004), to insure that adequate flow exists in the stream to allow specified diversions at gates. Binary variables are used in conjunction with flow-rate variables to determine the maximum amount of groundwater pumping that can be achieved while maintaining adequate streamflow. The problem is formulated so that a pumping decision is made in each month of the irrigation season (end of May, June, July and August) for each of the 16 pumping wells. The pumping decision is binary, that is, *GWM* decides if the pump should be on or off. If the pump is on it operates at a rate that is a function of the permitted pumping rate for that well. The objective function in the Bates Creek formulation is to maximize the total withdrawal from all wells over the irrigation season. This is equivalent to maximizing the sum of flow-rate variables weighted by the duration of pumping for each well.

Results from the *GWM* runs with the Bates Creek simulation model reveal the complexity of the relationship between pumping and stream flow. While an intuitive response to inadequate streamflow at a gate may be to cut pumping at the nearest well, the *GWM* results show that this is often not the best strategy. Pumping early in the season can have impacts on downstream gate flows late in the season. Pumping far upstream from the affected gate has an impact on both groundwater delivery in the current month and later months and on stream delivery of water to downstream gate in the current month.

The relationship between pumping and stream flow at a gate is quantified by *GWM* through response coefficients. These values give the change in stream flow at a surface diversion point per unit change in pumping at a well. *GWM* calculates these response coefficients for every combination of 24 stream flows (4 months at each of 6 gates) and 64 pumping rates (4 months at each of 16 wells) for a total of 1536 response coefficients. Figure 21 gives an example of the *GWM* output from the Bates Creek demonstration, which shows the effect of pumping of all wells on stream flow the Bates Creek Ditch headgate (gate no. 3) under test scenario 6.

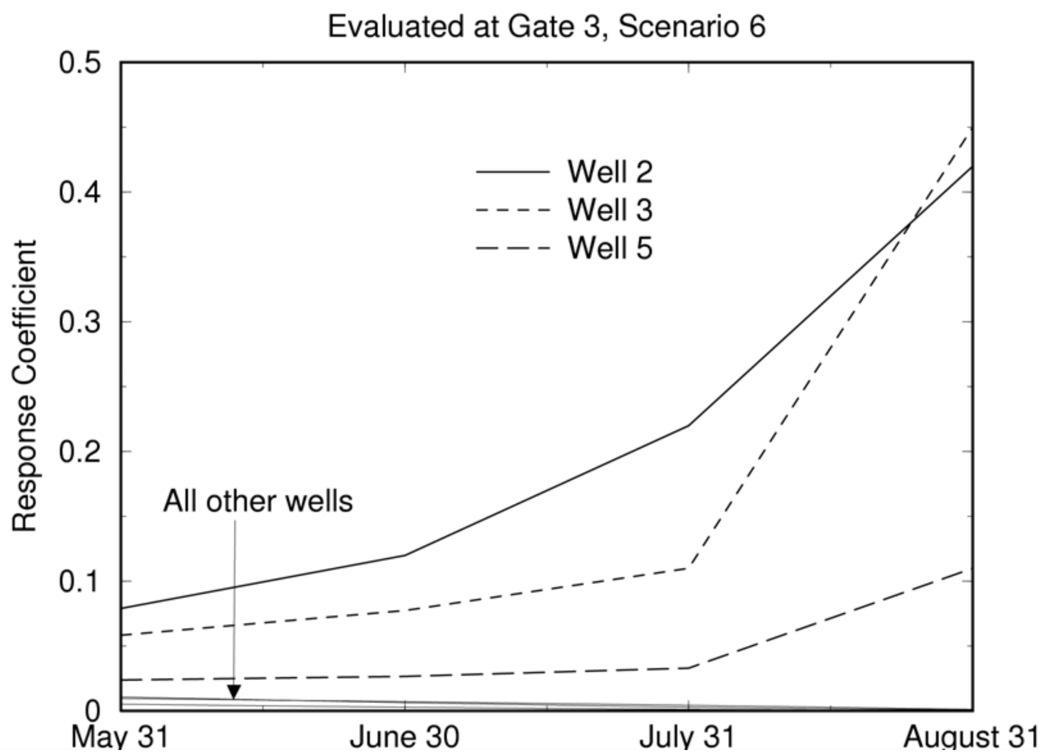

Figure 21: GWM Response Coefficients evaluated at the Bates Creek Ditch headgate for scenario 6.

GWM uses the calculated response coefficients to determine the combined impact of all wells pumping simultaneously on stream flows at all gates. This information is, in turn, used to determine the optimal combination of pumping rates that maximizes groundwater withdrawals while guaranteeing adequate stream flows for diversions for a given stream flow at the model domain boundary. For example, for the Scenario 6 results shown in Fig. 21, in order to insure that adequate water is present at the Bates Creek Ditch diversion, *GWM* determines that the best strategy is to turn off wells 2, 3 and 5. Note that wells 2 and 3 are the furthest upstream wells and farther from the diversion than 3 other wells (4, 6, 7) that are left on by *GWM*. Also note that the effect of pumping well 3 is intermediate early in the growing season, but the effect of pumping this well increases over the irrigation season, until it has the largest effect on headgate no. 3 at the end of August.

Conclusions

This report presents a model framework developed using readily available computational tools that can be used to identify a conjunctive-use management strategy. The tools used include the Groundwater Modeling System (*GMS*) model interface, USGS *MODFLOW* groundwater simulator and USGS *GWM* optimization code. As this study did not include collection of field data, we used data collected by others. The Wyoming State Engineer's office recommended that we demonstrate our modeling framework on the Bates Creek irrigation district southwest of Casper, Wyoming, near the confluence of Bates Creek and the North Platte River. The Wyoming State Engineer's office provided data for this area, and we used the previous modeling report by Glover (1983), for guidance on parameter values.

Before application of this modeling framework to a specific region, including the Bates Creek site used in this study, data collection is a necessity. Field studies in areas of interest should focus on collecting hydrologic data for a multi-year period in order to allow model calibration and verification over a range of seasons and climatic variation. These data would include stream flows, canal diversions and schedules, actual groundwater pumping flow rates and schedules, groundwater observation/monitoring wells, precipitation, snow melt, and meteorological variables.

Other parameters such as stream/canal bed infiltration losses and impeding layer properties are needed, as are observations of groundwater levels near streams. Land-surface data required include irrigation recharge areas, crops, rates of irrigation and times of application. These data together with the meteorological observations will allow estimation of consumptive use, leaching fraction, and groundwater recharge from irrigation. If surface return flows from irrigation are significant, they should be measured.

Studies and efforts underway to develop conjunctive management schemes in Nebraska and Colorado on this issue cover large irrigation areas near large rivers. Those efforts are quite expensive. While the cost for setting up an actual conjunctive management modeling tool on a specific irrigation district in Wyoming will be less, the need for data is the same. Without data, the modeling tool cannot be calibrated and verified.

We identified test scenarios based on the number of surface water diversions that could be satisfied given surface flows, based upon seniority. This is a unique aspect of this management problem. Management can only be performed to the degree that surface flows allow. In the absence of pumping, if there is only sufficient surface flow to meet the demands of a senior subset of surface diversions, it is nonsensical to manage pumping to optimize surface water diversions that cannot be met due to priority. To our knowledge, there is no widely accepted method to account for the effect of surface water priorities in an optimization scheme.

Our methodology assumes that all ground water rights in the study area are junior to all surface water rights. We did not take the date of well permitting into account in minimizing the impacts of individual wells on stream flow depletions. In effect, if any well is causing stream flow depletions that impinges on any surface water right, it must be shut off.

The GWM response coefficients indicate that in some cases, a well that is further from the stream diversion point can have a more significant and long-term effect on surface water diversions than a well that is closer to the diversion point. In this demonstration, there were instances when a well far from the stream had a significant effect on stream flow at a downstream location, later in the irrigation season. This example illustrates the utility of the approach.

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Appendix A

Telephone Script for Interviews

“Integrated Management of Groundwater and Surface Water Resources: Investigation of Different Management Strategies and Testing in a Modeling Framework”

Hello, I am __________, a research assistant for Melinda Harm Benson, an assistant professor at the University of New Mexico. She is conducting research on how different states manage ground and surface water resource issues. You have been identified as someone with expertise in the area of conjunctive water resource management. We are doing some interviews for a report that will be presented to the State of Wyoming’s State Water Engineer.

All information gathered during this interview will be kept confidential. If you would like additional information about how we intend to protect your privacy or about this research, you can contact Professor Benson at 505-277-1629, or you can email her at mhbenson@unm.edu.

Would you be willing to answer a few questions regarding on this topic?

If “no:” “thank you for your time. Goodbye.” (then hang up).

If “yes”: “Great, here are my questions—they need only take10 minutes or so of your time.”

4) What has been your experience with your state’s attempt to conjunctively manage ground and surface water resources and/or address conflict between surface and ground water users?
    1. Would you describe the experience as positive, negative?
    2. Why or why not?

5) Do you have any suggestions for how your state could improve its management of ground and surface water use conflicts?

6) Can you provide any examples of specific ground and surface water interactions in your state that inform your answers to questions 1 and 2?

7) What, in your opinion, is the greatest barrier to effective conjunctive management in your state?

8) Do you feel like your state has the necessary technical/hydrologic information necessary to implement its management scheme? Why or why not? What would improve the situation?

9) Is there anything else you would like to tell us about your experience with your state’s management of ground/surface water use conflicts?

Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstroms in Wyoming Using the Wyoming Cloud Radar

Basic Information

Title:	Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstroms in Wyoming Using the Wyoming Cloud Radar
Project Number:	2007WY39B
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Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Water Quantity, Climatological Processes, Hydrology
Descriptors:	None
Principal Investigators:	Bart Geerts

Publications

There are no publications.

Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming Using the Wyoming Cloud Radar

Final report for a three-year (Mar 2007 – Feb 2010)
U. S. Geological Survey and the Wyoming Water Development Commission grant
Dr. Bart Geerts, PI
4/28/2010

1. Abstract

This proposal called for 20 research flight hours of the University of Wyoming King Air (WKA) over the Snowy Range (Medicine Bow) mountains in Wyoming during the time of glaciogenic cloud seeding conducted as part of the five-year Wyoming Weather Modification Pilot Project (WWMPP). This pilot project, administered by WWDC and contracted to the National Center for Atmospheric research (NCAR) and Weather Modification Inc (WMI), involved seeding from a series of silver iodide (AgI) generators located in the Snowy Range. In Feb 2008 we conducted two WKA flights (8 flight hours). The remaining three flights were conducted in early 2009 (18 and 20 February and 10 March). Thus we have flown all flight hours (20) supported by this award. All five flights were a success in terms of both the target weather conditions and instrument performance.

2. Summary of the field work

All five flights in this campaign (referred to as WWDC Cloud Seeding) followed the general flight pattern shown in **Fig. 1**. We targeted west- to northwesterly wind, because in such flow the Snowy Range forms the first obstacle following a long fetch over relatively flat terrain (the Red Desert), because three generators (Barret Ridge, Mullison Park, and Turpin Reservoir) are aligned with the cross-wind flight legs (Fig. 1), and because this flow pattern does not interfere with NCAR's randomized experiment. This is because under such flow the seed generators are upwind of both the target and the control snow gauges. Aside from the along-wind leg (whose orientation depends on the prevailing wind, pivoting around GLEES), there are five fixed tracks roughly aligned across the wind. The NW-most of these five tracks is upwind of the three generators, and the 2^{nd}, 3^{rd}, 4^{th}, and 5^{th} tracks are about 2, 6, 9, and 13 km downwind of the generators. The first four legs are on the upwind side, while the 5^{th} one (tracking over GLEES) is mostly on the downwind side.

The pattern shown in Fig. 1 was repeated four times on several flights: the first two patterns had the seed generators off, and the last two patterns were flown with the seed generators on. On other flights we concentrated on the three most-downwind legs, and the number of patterns with seeding was increased at the expense of flight time without seeding (**Table 1**).

On all flights the Wyoming Cloud Radar (WCR) operated flawlessly, with three antennas (up, down, and forward-of-nadir). We recently discovered a small (0.60 m s^{-1}) downward bias in the Doppler vertical velocity from the up-looking antenna, on all flights. This correction was found after extensive comparisons with the down-looking antenna and with flight-level vertical wind data. On all flights we also had the up-looking lidar (Wyoming Cloud Lidar, WCL). On the last two flights, we also collected data from the recently-purchased down-looking lidar.

No less than 4 graduate students participated in the field campaign (Table 1), although only one graduate student (Yang Yang) is focusing her MSc research on the data from these five flights.

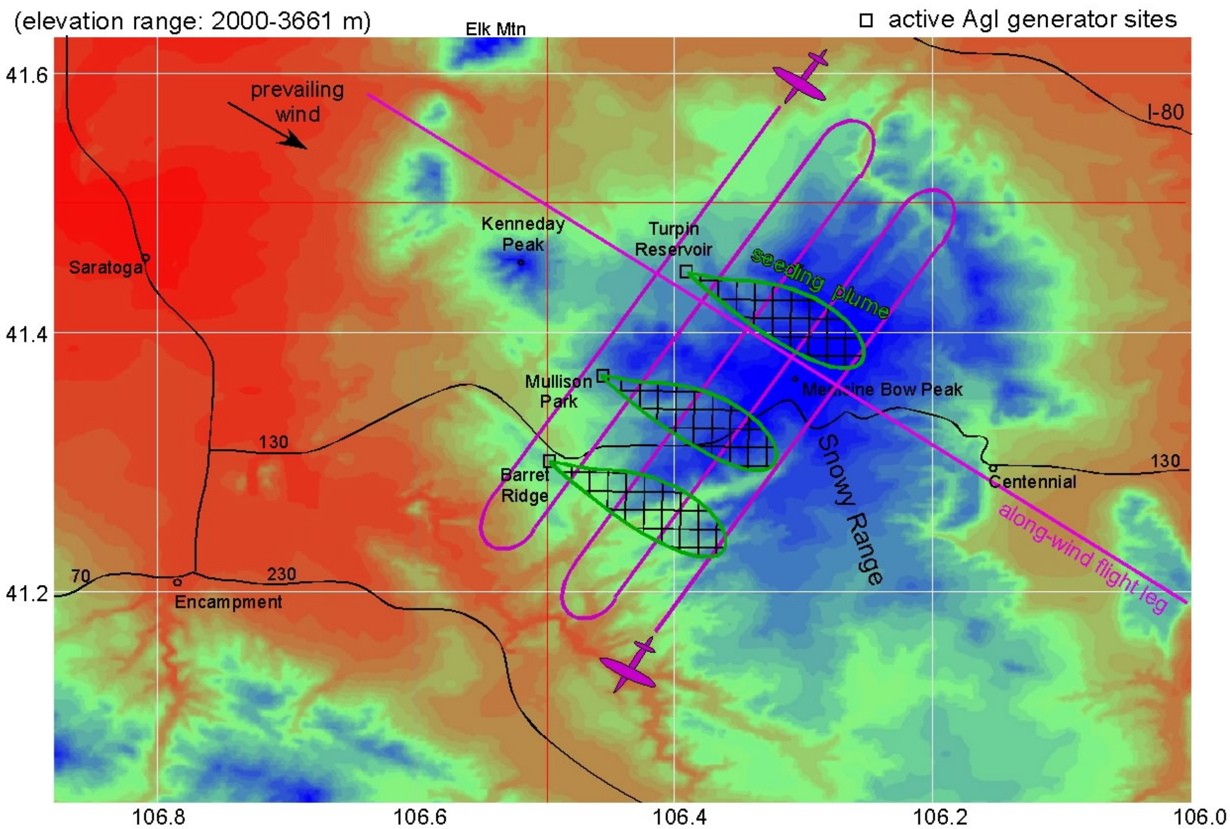

Fig. 1. A schematic of the WKA flight legs in the Snowy Range, over the AgI plumes (shown schematically with a green outline) released from three generators on the ground. The color background field shows the terrain. On all flights the flight level was set at 4,276 m (14,000 ft) MSL, the minimum permissible flight level over the terrain. The prevailing wind was from the NW. One flight leg was across the terrain (along the wind), the other 5 flight legs were roughly across the winds at various distances downstream of the three active AgI sources.

Table 1: Summary of the five WKA flights

date	flight scientist	nadir WCL?	# across-wind legs without seeding	# across-wind legs with seeding	14 kft wind direction (deg. from)	14 kft temperature (°C)
2/11/08	Bart Geerts	N	10	10	290°	-19
2/25/08	Qun Miao	N	10	10	293°	-18
2/18/09	Yonggang Wang	N	10	10	294°	-20
2/20/09	Yang Yang	Y	10	5	298°	-17
3/10/09	Mahesh Kovilakam	Y	5	15	280°	-23

List of graduate student participants

The following students participated in the flight planning, the flight itself, the flight debriefing and the writing of the flight report:

- Qun Miao, PhD student, advisor: Dr. Geerts: field training opportunity (he is currently a post-doc in the group)
- Yonggang Wang, PhD student, advisor: Dr. Geerts: field training opportunity
- Yang Yang, MSc student, advisor: Dr. Geerts: both essential to her research, and a field training opportunity (Yang Yang is partly funded by this WWDC/USGS grant)
- Mahesh Kovilakam, PhD student, advisor: Dr. Deshler: field training opportunity

3. Objectives and methodology

1. Document the planetary boundary layer (PBL) turbulence and natural precipitation enhancement on the upslope side of the Medicine Bow mountains. This work has been conducted mainly by Miao Qun, a post-doc in our group. This research has these elements:
    a. Conduct a spectral analysis of WCR vertical velocity near the ground, to see whether the turbulence is consistent with theoretical expectations in the inertial subrange.
    b. Generate colored frequency-by-altitude diagrams (CFADs) showing vertical velocity variance over all depths including above flight level.
    c. Stratify these CFADs as a function of ambient wind speed, maybe stability, using radiosonde data in WWDC Cloud Seeding.
    d. In order to determine whether streamers rise from the ground, estimate snow crystal trajectories from vertical-plane dual-Doppler analysis, which includes the actual fall speed.
    e. Isolate flight sections where WKA is in the PBL layer, and contrast these sections to upstream in-cloud sections (above the PBL), and
        i. in these sections, relate updrafts to LWC and ice crystal concentration;
        ii. also look at riming & aggregation using 2D-C, 2D-P data.
    f. Develop a composite reflectivity (and vertical velocity) structure across the mountain (following the method in Kusunoki et al., 2005, in MWR). The following steps are needed:
        i. obtain a typical terrain profile;
        ii. assign coordinates to reflectivity (and vertical velocity) from each cross-section (x,z), with x=distance from crest, z=height above ground;
        iii. compute average reflectivity (Z) and vertical velocity for each (x,z) and plot this over typical terrain profile;
2. Examine the impact of cloud seeding on reflectivity. This has been Yang Yang's MSc thesis research. She developed a composite reflectivity as function of distance from the seeder in each of the 4 downstream flight legs along the wind.

4. Principal findings

Preliminary results of the first two flights were presented at the joint 17^{th} joint American Meteorological Society - Weather Modification Association Symposium on Planned & Inadvertent Weather Modification in Westminster CO (Geerts 2008). In Feb 2010 a paper was submitted to *J. Atmos. Sci*. (Geerts et al. 2010), the most prestigious journal in its field. This paper is still in review, but the reviewers' comments are relatively minor. And in April 2010, Geerts was an invited keynote speaker at the Annual Weather Modification Association meeting in Santa Fe NM. In that talk, he presented the main findings of the *J. Atmos. Sci*. paper.

Here are the main results from the five flights conducted under this grant:

1. With so much natural variability it is very difficult to detect a seeding signature. Nearly 50% of the flights were in unseeded conditions (Table 1), and the 1^{st} of 5 across-wind legs was upstream of the mountain (Fig. 1). These choices were made to detect a seeding signature by contrasting seeding to no-seeding patterns. Clearly the actual location of the plumes is uncertain. We do have excellent wind profile data from VAD analyses in the turns between across-wind legs. Still, the plumes may meander considerably in time. <u>Visual inspection of WCR data along each leg indicates that there is no apparent change in radar reflectivity downwind of the AgI generators</u>. Some boundary-layer eddies make it up to flight level, especially along the 4^{th} leg going over the highest peaks. In these eddies, there appears to be <u>no reduction in supercooled liquid water content nor a increase in number of ice crystals</u> in areas downwind of the AgI plumes, compared to eddies in similar locations but clearly away from the AgI generators, or collected before the generators were turned on.
2. Deep PBL turbulence along the upslope section of the mountain was present on all days. The depth of PBL mixing was about 1 km, ranging from 600 m on more stable days to 1300 m and beyond on the less stable days. <u>This turbulence effectively mixes the AgI aerosol released from ground generators into an orographic cloud where most of the supercooled water naturally resides</u>, in other words, ground-based seeding of orographic clouds is more effective than airborne seeding. Since this turbulence occurs within cloud, precipitation growth though riming is likely in turbulent eddies whose updraft speed far exceeds the average ascent rate over the terrain. In fact this growth is suggested by the increase of the WCR reflectivity along the upwind slope of the Snowy Range, near the surface, in a layer that is sometimes disconnected from the snow layer aloft. The flight-level data were usually collected above the BL, but in some sections we were low enough to collect cloud microphysics data within the PBL, and they show large ice crystal concentrations and evidence of riming. Note that PBL turbulence would also mix ice particles generated near the ground into cloud (natural cloud seeding). Such ice particles could result from blowing snow or from the splintering of supercooled water along rimed surfaces on the ground. The main evidence for this is the increase in reflectivity along the upwind slope, above cloud base, in the PBL, by local growth of ice crystals (Vali et al., 2008). This needs to be examined further.
3. We flew two additional flights in March 2009, funded by a follow-up WWDC/USGS grant (referred to as Cloud Seeding II). On the last of these flights, on 3/25/09, <u>there is a hint of a "seeding signature"</u> downwind of mainly the middle generator (Mullison Park, see Fig. 1). This signature includes reduced flight-level liquid water and increased concentration of ice crystals (**Fig. 2**). It also includes increased radar reflectivity below flight level, and more rapid attenuation of the nadir lidar backscatter power. The high depolarization ratio indicates

that this attenuation in the high-reflectivity plume is due to ice crystals. Three other passages along the same flight leg shows repeatability, that is, the seeding signature is present in four successive legs during seeding, but absent on the first passage, before the AgI generators were turned on.

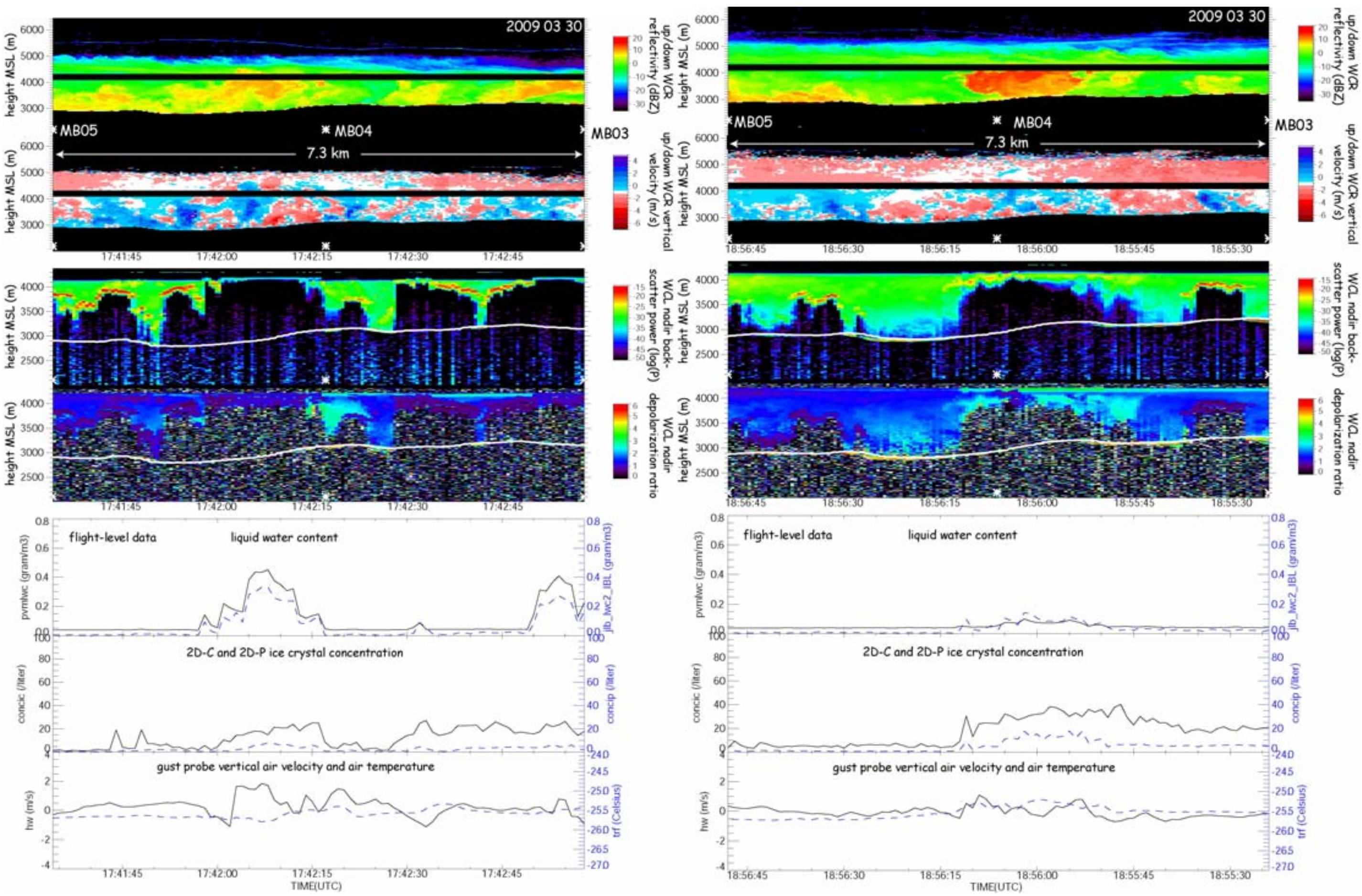

Fig. 2: Comparison of flight-level and remote-sensing data along flight leg #3, located 6 km downwind of the AgI generators (Fig. 1), on 3/25/2009. The AgI generators were off during WKA passage on the left, and on for the flight leg on the right. The top two panels show WCR reflectivity and vertical velocity, above and below the aircraft. The black stripe in the middle is the flight level, and the ground is evident as the sloping surface below flight level. The next two panels give nadir WCL backscatter power and depolarization ratio. The bottom three panels show flight-level data.

5. Further plans

So far we conducted seven flights over the Snowy Range, five funded under the present project and two under Cloud Seeding II. Following the review of the *J. Atmos Sci.* paper (Geerts et al. 2010), we are preparing a paper dealing with the importance of PBL turbulence on orographic precipitation (Geerts and Miao 2010), and another paper further exploring seeded cloud properties with flight-level data (Yang et al. 2010).

We also have two other orographic precipitation studies planned. First, Dr. Geerts is the PI of the SOLPIN component of the current University of Wyoming NSF EPSCoR proposal, called “Earth System Interactions in Complex Terrain”. The SOLPIN (Simulations and Observations of Land-Precipitation Interactions) component is worth about $6 million, plus $2 million in UW matching. Both winter and summer orographic precipitation will be studied, using experimental data and numerical simulations. Second, Dr. Geerts is the PI in a large, collaborative proposal, known as ASCII (AgI Seeding of Cloud Impact Investigation). This proposal in preparation is to be funded by NSF and, if funded, to be conducted in the Medicine Bow Mountains in the winter of 2011-12, as part of the WWMPP. The emphasis here is on the cloud microphysical effects of glaciogenic seeding in cold orographic clouds.

The following new elements will be included in these proposal(s):

a. fly on a windy clear-sky day (following a snow storm) to look at the vertical distribution of blowing snow mixed into the PBL;
b. fly a mission downwind of seed generators under conditions unsuitable for ice particle generation near the ground, but suitable for seeding;
c. include crystal habit / riming measurements at the ground, preferably on the upwind side of the mountains
d. examine diurnal variation of PBL turbulence, and changes in stability & cloud depth in association with the passage of a frontal disturbance;
e. examine a broader parameter space, in terms of cloud depth and ambient temperature by including snowstorms advected from the southwest.

6. Significance

Our findings are believed to be very significant. Geerts was an invited keynote speaker at the Annual Weather Modification Association meeting in Santa Fe NM in April 2010. At that meeting, Arlen Huggins, a veteran researcher in weather modification, mentioned our work as one of the most significant achievements in glaciogenic seeding efficacy research in the past decade.

7. Publications

- Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: The impact of glaciogenic cloud seeding on snowfall from winter orographic clouds. *J. Atmos. Sci.*, in review.
- Geerts, B., and Q. Miao, 2010: Boundary-layer turbulence and orographic precipitation growth in cold clouds: evidence from vertical-plane airborne radar transects. *Mon. Wea. Rev.*, in preparation.

8. Presentations

(a) with abstracts:

- Andretta, T., and B. Geerts, 2008: Snowfall in mountain lee convergence zones: a case study. 13th Conference on Mountain Meteorology, Whistler, BC, 11–15 August 2008. [Thomas Andretta is a PhD student under Dr. Geerts]
- Geerts, B., 2008: Impact of surface interaction and cloud seeding on orographic snowfall: A downlooking airborne cloud radar view. Oral presentation at the 17th joint American Meteorological Society - Weather Modification Association Symposium on Planned & Inadvertent Weather Modification, Westminster, CO, April 21-25, 2008.

- Geerts, B., J. Snider, G. Vali, and D. Leon, 2008: Orographic precipitation enhancement by boundary-layer turbulence: a vertically pointing airborne cloud radar view. 13th Conference on Mountain Meteorology, Whistler, BC, 11–15 August 2008.
- Vali, G., B. Geerts, J. Snider, and D. Leon, 2008: Surface source of ice particles in mountain clouds. 15th International Conference on Clouds and Precipitation (ICCP), 7-11 July 2008, Cancun, Mexico.
- Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: Vertically-pointing airborne radar observations of the impact of glaciogenic cloud seeding on snowfall from orographic clouds. Weather Modification Association meeting, Santa Fe NM, 21-23 April.

(b) without abstracts

- Geerts, B.: A series of progress reports presented at the Wyoming Cloud Seeding Pilot Project Advisory Team meetings in Cheyenne or Lander WY (May 07, Oct 07, Feb 08, Dec 08, Jul 09, and Dec 09).
- McIntyre, H.: NASA06 observations of orographic precipitation types over the Snowy Range under different stability and flow regimes, UW-NCAR RAL workshop in Boulder, CO, March 6, 2007.

9. Students supported

Three graduate students have been supported by this grant:

Heather McIntyre (MSc student) was supported by this grant in Spring semester 2007, but she failed to maintain a 3.0 GPA and left the program in May 2007.

Thomas Andretta started in late August 2007, although coursework and PhD Qualifying Exam were his main pre-occupations until May 2008. He participated in the February 2008 cloud seeding validation field experiment. Unfortunately, in June 2008 he decided to switch research topics and focus on natural snowfall processes in mountain lee convergence zones. His project was funded by a UW NASA Space Grant Consortium fellowship between Aug 2009-May 2010.

Yang Yang (MSc student) joined us from China in August 2008, and was supported by this grant. Her father and grandfather have been involved in cloud seeding research in China, and she has strong credentials, so we are pretty excited to bring her on-board. She is expected to graduate in May 2011.

One post-doctoral scientist, Dr. Qun Miao, has also been partly supported by this grant. He was essential in the data analysis leading to the *J. Atmos. Sci.* paper (Geerts et al. 2010). He left the group in Jan 2010 to assume a faculty position in Ningbo University. He will be back in summer as visiting research scientist.

Finally, two other PhD students (Yonggang Wang and Mahesh Kovilakam) participated in the field campaign in early 2009 (see Table 1). This participation has given them invaluable experience in airborne field research.

Weather Modification Impacts and Forecasting of Streamflow

Basic Information

Title:	Weather Modification Impacts and Forecasting of Streamflow
Project Number:	2007WY40B
Start Date:	3/1/2007
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Water Quantity, Climatological Processes, Hydrology
Descriptors:	
Principal Investigators:	Glenn Tootle

Publications

There are no publications.

Weather Modification Impacts and Forecasting of Streamflow

PIs: Glenn Tootle (UW and Univ. of Tennessee) and Tom Piechota (Univ. of Nevada)
Graduate Students (UW and Univ. of Tennessee): Cody Moser, Ty Soukup, and Oubeid Aziz
Post-Doctoral Research Assistant (Univ. of Nevada): Haroon Stephen
Final Report for a Three Year Project – March 2007 thru February 2010

Executive Summary and Research Results

On behalf of the graduate research assistants (Cody Moser, Ty Soukup and Oubeid Aziz), post-doctoral research assistant (Haroon Stephen), Co-PI (Tom Piechota) and the PI (Glenn Tootle), we hereby submit our final report *Weather Modification Impacts and Forecasting of Streamflow*. The research team would also like to acknowledge Shaun Wulff (UW Department of Statistics) for his assistance.

The scientific objectives of the proposed three-year research project were to:

1. Identify and evaluate snowpack, unimpaired streamflow, soil moisture and air temperature datasets in weather modification target areas within the state of Wyoming. *The North Platte River Basin was selected given the weather modification efforts in the basin. Chapter One and Chapter Two of the final report evaluated and utilized datasets in this basin.*
2. Examine relationships between snowpack and streamflow, including the impacts from the previous Fall season soil moisture (antecedent moisture conditions) and following Spring-Summer season air temperature on resulting streamflow from snowpack. This includes determining the optimum (i.e., highest correlation) relationships (period and lag time) between snowpack and streamflow. *Chapter One evaluated the relationships between snowpack, streamflow and antecedent soil moisture in the North Platte River Basin and determined optimum relationships. This included which season and the lag between the predictor and predictand.*
3. Utilizing the optimum relationships, develop statistically based models (regression) for snowpack and resulting streamflow and apply the models to quantify streamflow increase due to snowpack increase as a result of weather modification. *Chapter One developed regression equations, relating snowpack to streamflow, in the North Platte River Basin. These regression equations can be utilized to estimate increases in streamflow based on snowpack increases due to weather modification. At the time of this final report, NCAR has not provided estimates for increased snowpack. Chapter One was the basis of Cody Moser's UW Department of Civil Engineering thesis and was published in the below referenced ASCE EWRI proceedings.*
4. Utilizing relationships between snowpack and streamflow, evaluate statistically based models, including regression and non-parametric approaches, and develop forecasts of streamflow including exceedance probability, forecast skill and uncertainties. *Chapter Two of the final report evaluated long lead-time forecasts of streamflow in the North Platte River Basin, using climate (Sea Surface Temperatures and 500mb pressures). A non-parametric (exceedance probability) streamflow forecast was developed for several*

streamflow stations in the North Platte River Basin. Chapter Two was the basis of Ty Soukup's UW Department of Civil Engineering thesis and was published in the below referenced Journal of Hydrology.

The research provided outstanding training and support for the above mentioned graduate students. All three graduate students have completed their master's degree. Ty Soukup is currently employed at Tri Hydro in Laramie, Wyoming while Cody Moser and Oubeid Aziz are currently PhD students at the University of Tennessee.

The results of the research have been published in a conference proceedings and a peer-reviewed journal:

Moser, C., T. Soukup, G. Tootle and T. Piechota, 2008. An Expert System Approach to Improve Streamflow Forecasting in the North Platte River Basin, Wyoming, USA. Proceedings of the *ASCE World Water & Environmental Resources Congress 2008*, May 11-17, 2008, Honolulu, HI.

Soukup, T., O., Aziz, G. Tootle, S. Wulff and T. Piechota, 2009. Incorporating Climate into a Long Lead-Time Non-parametric Streamflow Forecast. *Journal of Hydrology*, 368(2009), 131-142.

In addition to numerous local presentations including the WWDC/WWDO Weather Modification Technical Advisory Committee meetings, the research was presented at the 2008 ASCE EWRI Conference in Honolulu, HI.

The results of the research made several contributions including:

- As expected, there are strong relationships between snowpack (Snow Water Equivalent) and streamflow in the North Platte River Basin. However, the inclusion of Antecedent Soil Moisture resulted in slight improvement in streamflow forecasting skill in the basin and should be considered in future forecasts.
- The use of Sea Surface Temperatures and 500mb pressures resulted in the ability to provide a skillful long lead-time (three to six months) forecast of streamflow in the North Platte River Basin. The identification of these climatic teleconnections may provide important information prior to the winter season during weather modification operations.

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CHAPTER 1 - Improving Streamflow Forecasts by Incorporating Antecedent Soil Moisture

ABSTRACT

A study of incorporating antecedent (preceding) soil moisture into forecasting streamflow volumes within the North Platte River Basin is presented. By integrating antecedent soil moisture as a predictor to forecast streamflow, processes that determine the amount of streamflow, such as infiltration and runoff can be better accounted for. Current Natural Resource Conservation Service (NRCS) forecasting methods are replicated and a comparison is drawn between current NRCS forecasts and proposed forecasting methods. Current predictors used by the NRCS in regression based streamflow forecasting include precipitation, streamflow persistence (previous season streamflow volume) and snow water equivalent (SWE) from SNOTEL (snow telemetry) sites. Proposed methods include utilizing antecedent soil moisture as a predictor variable in addition to currently used predictors and extending the forecast period of record. By extending the period of record, an expert (decision) system is used to segregate data based on antecedent soil moisture conditions (e.g., dry, wet or normal). Correlation techniques are applied to determine ideal predictors. Principal component analysis and stepwise linear regression is applied to generate streamflow forecasts and numerous statistics are determined to measure forecast skill and check for violation of model assumptions. The results show that, when incorporating antecedent soil moisture, overall model skill improved. More importantly, "poor" forecasts (i.e., years in which the NRCS forecast differed greatly from the observed value) were greatly improved. The research shows the need to increase monitoring and the collection of soil moisture data in mountainous western U.S. watersheds.

INTRODUCTION

Streamflow forecasting is the process of predicting a seasonal volume of water at a specific site (gauge) location at a specific time. Generally, in mountainous regions of the western U.S., the season of interest is the spring-summer season when natural supply levels decrease and demand increases due to seasonal influences. The NRCS, in cooperation with the National Weather Service (NWS), issue water supply forecasts for over 750 points in the western U.S. near the first of the month between January and June each year. These forecasts assist water managers/users for future planning according to the forecasted amount of water available. While these forecasts are produced monthly, this study focuses on forecasting the season of interest, which is the cumulative April-May-June-July streamflow volume.

Water managers operate with a shrinking margin of error, facing increasingly complex and competing demands while trying to retain flexibility to adapt to hydro climatic conditions (Pagano et al. 2004). The primary objective of these forecasts is to minimize risk and uncertainty for water managers, therefore creating more efficient use of a scarce resource. Thorough understanding of forecast performance helps decision makers determine when and how much to rely on forecasts as well as how to respond to expected climatic anomalies (Hartman et al. 2002). Over allocated supplies and increasing demands require the precision management of water. While the NRCS has been forecasting water supplies for close to 70 years, it is evident that the physical and demographic landscapes of the Intermountain West are changing (Tom Pagano, unpublished Snow Survey Centennial Newsletter, September 25, 2006). Hartman et al. (2002)

reveals how streamflow forecasts can be more effectively used if scientists look at the user's perspective.

While the NWS use a comprehensive set of models and hydrologic techniques, NRCS forecasts are produced using statistical approaches such as multiple linear regression models. These regression based forecasts rely on measurements of current snowpack, antecedent streamflow and autumn precipitation (Pagano and Garen 2006). The regression models suggest a relationship between predictor variables (precipitation, snow water equivalent, antecedent streamflow, etc.) and the predictand (streamflow volume of interest). Several techniques were developed by Garen (1992) to significantly improve forecast accuracy when using regression models. These techniques include: (1) basing the regression model only on data known at forecast time (no future data); (2) principal components regression; (3) cross validation; and (4) systematic searching for optimal or near-optimal combinations of variables (Garen 1992). Historical practice in forecasting often included variables in regression equations that described future precipitation amounts. The research of Stedinger et al. (1988), Koch (1990) and Garen (1992) proved that use of future variables (variables that describe future snow accumulation or precipitation) and substitution of averages reduced forecasting accuracy, especially early in the forecasting season. Therefore, research presented here does not use future variables, but only variables known at the time of the forecasting process. Currently, the NRCS combines manual measurements, an ever-expanding network of SNOTEL sites, and powerful advances in information technology and data communication to monitor the pulse of western snowpacks and water supplies (Tom Pagano, unpublished Snow Survey Centennial Newsletter, September 25, 2006). This information is communicated to users through innovative new products.

Prior to developing a forecast model, it is vital to analyze predictors. This includes creating and maintaining an extremely high quality historical dataset, subjected to the most rigorous screening and data quality testing (Pagano et al. 2005). As stated by Garen (1992), "A more robust, accurate and consistent forecasting equation can be obtained by having several sites for the same data type and time in the equation." Currently, the predictors obtained for NRCS streamflow forecast models are obtained from remote sensing data sources. Due to the relative newness of these remote sensing sites, the period of record used by the NRCS to develop a streamflow forecast is relatively short (i.e., limited period of record).

The motivation of this research evolved after a meeting with the NRCS in Portland, Oregon (Tom Pagano, personal conversation, October 22, 2007) regarding the forecasting of streamflow in Upper North Platte River Basin. First, the NRCS stated that "The Upper North Platte River Basin was one of the more challenging regions to forecast in the western U.S." An additional question posed was "Is a there a way to increase forecast skill for years in which current NRCS forecasts result in a 'poor' forecast (i.e., NRCS forecast is much different than actual) while improving overall model skill?" The challenge posed to researchers is to achieve these two objectives (improve overall model skill and improve "poor" year forecasts) while constrained to using current NRCS forecasting methods (principal component stepwise linear regression).

In addition to the traditional predictors (snow water equivalent, precipitation, and antecedent streamflow) currently used in streamflow forecast models, this study proposes the incorporation of National Oceanic and Atmospheric Administration (NOAA) climate division soil moisture data. Although soil moisture data is recorded by enhanced SNOTEL (NRCS) sites, antecedent soil moisture (ASM) is not currently used in coordinated NRCS-NWS streamflow forecasts within the North Platte River Basin. Past research that has incorporated soil moisture as a predictor in streamflow forecasting include Day (1985) and Aubert et al. (2003). In addition to incorporating (adding) ASM as a predictor, this research proposes a novel approach in the development of an expert (decision) system based on ASM. This decision system is based on segregating ASM data into three specific categories: wet, normal, and dry. Each category has its own regression equation, utilizing current NRCS methods (principle component stepwise linear regression). It is important to recognize that the development of an expert (decision) system requires increasing the period of record (i.e., extended period of record) to include data (i.e., manually obtained) prior to the deployment of remote sensing collection tools.

Therefore, the contribution of this research is the identification of a valuable predictor (ASM) and a new framework (decision system based on ASM) for improving poor NRCS streamflow forecasts while maintaining overall model skill in the North Platte River Basin. The results support the need to increase monitoring and the collection of soil moisture data, especially in mountainous western U.S. watersheds in which snowpack is the primary driver of streamflow runoff. The collection of soil moisture data will ultimately provide a useful database to improve streamflow forecasts in these regions.

WATERSHED DESCRIPTION

The North Platte River is a tributary of the Platte River, which is approximately 1,094 kilometers in length. The North Platte River originates in Colorado where it flows north into Wyoming, and then flows east to Nebraska (Figure 1.1). Three major reservoirs in Wyoming along the North Platte River are Seminoe, Pathfinder, and Glendo. Present use and future development of water resources in the North Platte River Basin are controlled by the 1945 Supreme Court Decree for the North Platte River.

The North Platte River watershed is predominately located in mountainous regions of Colorado and Wyoming. Thus, most of the annual streamflow is attributed to melting snowpack that has accumulated during winter and early spring months in mountainous headwater regions. Pagano and Garen (2006) suggest that snowmelt provides approximately 80 percent of the streamflow in the western United States. The delay between the time that snow accumulates and then melts creates the opportunity to generate an estimate of the actual amount of runoff.

DATA

Available datasets used to forecast streamflow include antecedent streamflow (streamflow persistence), snow water equivalent, precipitation and ASM.

Streamflow Data

The data used in this study comes from two streamflow stations (USGS 06620000 and USGS 06625000), which are located the Upper North Platte River Basin. The data can be obtained from the United States Geological Survey (USGS) NWIS website (http://waterdata.usgs.gov/nwis/rt). Each of these stations is recognized as being unimpaired (Wallis et al. 1991) and a current forecast for each station is provided by the NRCS. USGS streamflow station 06620000 is the most upstream (southern) station. The station's elevation is 2,380 m above sea level and has a drainage area of 3,706 square kilometers. USGS station 06625000 is located on a downstream tributary (Encampment River) and is 2,124 meters above sea level with a drainage area of 686 square kilometers. See Figure 1.1 for a detailed location map covering the region of study. The USGS provides daily, monthly, and annual mean streamflow in cubic feet per second (cfs). Total monthly streamflow in cubic meters for April-May-June-July (AMJJ) is calculated using appropriate conversions. Antecedent (January-February) streamflow volume, a commonly used predictor in NRCS forecasts, is also utilized.

Snow Water Equivalent (SWE) Data

The NRCS National Water and Climate Center provides snow water equivalent data (in inches) for the western United States (http://www.wcc.nrcs.usda.gov/snow/). Snow water equivalent data is distinguished into 2 groups: snow course & SNOTEL. Early SWE data (snow course) was recorded manually, and SNOTEL data is published in real-time through use of remote sensing stations. Snow course data in the western U.S. dates as far back as 1906 while SNOTEL data in the North Platte River Basin dates back to the early 1970's depending upon when the digital sensors in the station were installed. Within the North Platte River Basin, there are a total of nine SWE stations that are located within and adjacent to the drainage basin (Figure 1.1). These stations provide accumulated precipitation, snow depth, snow water equivalent, temperature, and soil moisture (for enhanced stations) data. April 1 SWE (converted from inches to centimeters) is used as a predictor in the current research.

Precipitation Data

Current NRCS methods use only precipitation data from SNOTEL sites (limited record). Precipitation data is also available from the Western Regional Climate Center (WRCC) website (http://www.wrcc.dri.edu/) using monthly precipitation totals. One precipitation station has data dating back to the year of interest (1940) for the proposed extended record analysis. This station is located in Steamboat Springs, Colorado and has monthly data dating back to 1908. Average precipitation data was obtained for the Steamboat Springs, Colorado station (converted from inches to centimeters) for the period of October through December of the previous year and January through March of the forecasted year.

Antecedent Soil Moisture Data

Data for soil moisture was obtained from the National Oceanic and Atmospheric Administration (NOAA) website (http://www.cpc.ncep.noaa.gov/soilmst/). NOAA soil moisture data is estimated by a one-layer hydrological model (Huang et al. 1996, van den Dool et al. 2003). The model takes observed precipitation and temperature and calculates soil moisture, evaporation and runoff. A study in eastern Oklahoma resulted in a maximum holding capacity of 760 mm of water using a common porosity of 0.47 which implies a soil column of 1.6 meters. Because this soil moisture is modeled data, there is only one value for the entire climate division. Of the 344 climate divisions in the U.S., one soil moisture dataset is within the North Platte River Basin. This station is located in climate division 10 within the state of Wyoming and the data covers an area of 61.6 square kilometers (Figure 1.1). Accessible monthly soil moisture data is available from 1932 to 2005 (74 years). Average ASM for this station in mm (for the period of October through December of the previous year and January through March of the forecasted year) was obtained. The authors acknowledge that NOAA climate division soil moisture contains many uncertainties. However, the primary hypothesis of this research is that ASM is a useful predictor for streamflow forecasting. Currently, this is the best available dataset that provides an extended period of record. Soil moisture data from enhanced SNOTEL (NRCS) stations is relatively new and dates back only a few years. Due to the lack of record, this data is not used in this study.

FORECAST METHODOLOGY

Limited Record (Current NRCS Methods)

The NRCS has developed a Visual Interactive Prediction and Estimation Routine (VIPER) to forecast streamflow. This forecast application gathers all data in real-time directly from the source. Linked with both historical and real-time data, the hydrologist specifies a list of predictor sites for a specified streamflow gage, the type of analysis desired (principal component stepwise linear regression is the most common NRCS method to forecast streamflow in the North Platte River Basin), and equations are automatically developed and the forecast produced in real-time (Tom Pagano, unpublished Snow Survey Centennial Newsletter, September 25, 2006). Pagano's 2006 newsletter details the methodology used for these forecasts and the current research replicates these methods. This real-time approach is very efficient, but has the disadvantage of using only data that has been recorded by digital sensors (limited period of record). Data of this type varies in relation to when the SNOTEL site was installed. The first of these SNOTEL sites in the North Platte River Basin was established in the early 1970's, which limits the digital data that can be used in producing forecasts. For varying streamflow stations, this period of record varies depending upon the available SNOTEL data. In this study, the forecasted period of record (limited) used by the NRCS for USGS streamflow station 06620000 is 1979-2005 (27 years) while 1983-2005 (23) years is the period of record for USGS 06625000. Within the VIPER interface, various types of streamflow transformations can be applied to improve forecast skill. Transforming streamflow data can be a very valuable tool to increase forecast accuracy, especially when recorded streamflow is non-linear. These transformations include square root, cube root, logarithmic, and natural logarithmic. The type of transformation producing the most accurate forecast (R^2) is chosen. USGS 06620000 is most accurately forecasted using a square root transformation. This process involves transforming the streamflow data, running principal component stepwise regression, and finally transforming the streamflow volume back to the proper scale (in this case cubic meters). USGSS 066250000 is most accurately forecasted when the streamflow data is left untransformed.

Current NRCS Methods Incorporating ASM

The previous NRCS forecast methods for the limited record are now replicated with ASM added as a predictor into the principle component analysis. The same transformation, period of record and predictors are used. Results are then analyzed to determine if the addition of ASM results in an increase in forecast skill.

Extended Record (Applying NRCS Methods)

Extending the period of record (back to approximately 1940) is required to develop an expert (decision) system. By extending the forecast period of record, increased variability in hydrologic predictors (and response) can be accounted for and sufficient data is available to develop an expert system. In this region, streamflow data was first measured in the early 1940's. Therefore, data including precipitation, snow water equivalent, and soil moisture in the North Platte River Basin is also required dating back to the same period. For this analysis, ASM is not included because this evaluation was designed to replicate current NRCS forecast methodology for the extended period of record.

Identifying Predictors (Extended Record)

Predictors are identified for the extended period of record. Seasonal streamflow and SWE correlation values are first analyzed. Next, moving time (10, 20, 25, and 30 years) window correlations between streamflow and SWE is performed, as in Biondi et al. (2004). This ensures that reliable and consistent SWE data sets are used (i.e., stability throughout the record) given the uncertainties (e.g., prolonged equipment malfunction, equipment calibration, human error) in the collection of SWE data for various periods of record. Finally, correlation values between snow course/streamflow and SNOTEL/streamflow are analyzed. This will (or will not) confirm that the relationship between snow course/streamflow is similar to the relationship between SNOTEL/streamflow A minimum difference between snow course/streamflow and SNOTEL/streamflow correlation values is essential because stability throughout the period of record is needed to extend the model back to the early 1940's.

A visual inspection of the streamflow and SWE correlations resulted in the following "rules" for the inclusion of the SWE station as a predictor. First, the overall correlation value between SWE and streamflow must exceed 0.55 to be included as a predictor. Second, if any of the moving time window correlations resulted in a negative value, the SWE station was not included. Finally, the comparison between snowcourse/streamflow and SNOTEL/streamflow correlation values must not differ by more than 0.15 to be included.

Precipitation records dating back to the period of interest are for the most part non-existent in the North Platte River Basin. The only location that precipitation data is available dating back to the early 1940's is in Steamboat Springs, Colorado. The previous "rules" are applied to precipitation and streamflow. Finally, streamflow persistence (JF) is also correlated against AMJJ streamflow. After determining the most appropriate predictor variables to extend the period of record, the same methodology used by NRCS (principal component stepwise linear regression) is performed for the extended period of record.

Applying Current NRCS Methods Incorporating ASM

The next analysis adds ASM as a predictor into the principle component analysis. The forecast timeline is kept consistent and previous predictor variables identified are not changed. Additionally, the same forecast methodology is used. This process determines if incorporation of ASM as a predictor results in improved streamflow forecast skill for the extended period of record.

Expert (Decision) System Incorporating ASM

The last analysis in this research segregates predictor variables (i.e., expert system) based solely on ASM (e.g., wet, dry, normal). This requires performing a simple statistical analysis to determine the average and standard deviation of ASM data for the season and record of interest. Wet years are defined as those whose soil moisture is 1.25 standard deviations (σ) above average, and similarly, dry years are defined as those whose soil moisture is 1.25σ below the overall average. Remaining years are considered normal years. The expert system value of 1.25σ is chosen because it produces higher forecast skill when compared to expert systems that group the data based on 0.75σ and 1σ. Using a standard deviation higher than 1.25 is not investigated since it would result in very few extreme years. After grouping the data into the appropriate categories using ASM conditions (wet, normal, dry), principle component stepwise linear regression is performed individually on the three sets of data (wet, normal, dry). This analysis results in three separate regression equations that are used to forecast streamflow based on ASM conditions.

"Poor" NRCS Forecasts

A "poor" streamflow forecast is one that predicts a streamflow volume that is much different than the actual (observed) volume. For this research, a "poor" forecast is determined by ranking (worst to best) each year and selecting the upper quartile (25%) of worst forecasts and defining them as "poor" forecasts. There are a variety of reasons that lead to "poor" streamflow forecast for a particular year. They include: data unavailability, unexpected precipitation, unforeseen drought conditions, and climate change. Any one of these, or all of them, are possible reasons a "poor" forecast is produced. Implications of "poor" streamflow forecasting include: inefficient management/allocation of water, water managers having little confidence in forecasts, and reduced credibility of the forecaster. The hypothesis of this research is that the incorporation of ASM will reduce the "number" of "poor" forecasts while maintaining overall model skill. The physical basis of this hypothesis is that ground surface conditions (wet, dry, normal) will influence the amount of runoff. Simply put, the same snowpack and precipitation for wet ground surface conditions will produce more runoff than dry ground surface conditions.

Statistical Analysis

In forecasting, problems with intercorrelation arise when predictor variables are highly correlated with other predictor variables. For example, antecedent streamflow correlates highly with precipitation and snow water equivalent. The most satisfactory and statistically rigorous way to deal with intercorrelation, and the method applied in this study, is to use principle component regression (Garen 1992). Principle component regression is a useful technique for addressing multicollinearity problems and can yield better predictors (Khattree and Naik 2000). An important property of the principle components is that they are uncorrelated (Anderson 2003). Thus, there are no problems with multicollinearity. The number of components retained in the equation depends upon how many of the components have statistically significant regression coefficients. It is also necessary to determine which principal components to use in the regression equation (Garen 1992). Garen (1992) used a standard t-test to determine significance of the regression coefficient for the component. A similar method, presented in this study, is the use of forward stepwise linear regression to determine the number of principle components to include in the regression model. Forward stepwise regression determines what predictors explain a significant amount of the variance, starting with the predictor that explains the most variance while adding/removing any predictors that do/do not significantly improve the fit. For this study, a stepwise linear regression F-value of 4 is used. For a two-sided test with alpha=0.05 (95% significance) and sample sizes of 20 or more, the critical value for the standard t-test is close to 2. Squaring this t-value produces a critical partial F-value near 4.

Numerous predictive statistics can be calculated to determine the skill of a principle component regression model. These include the standard error of the regression, R^2, adjusted R^2, the PRESS statistic, and the predicted R^2. The standard error of the regression (S) is used to describe model fit and is equivalent to the square root of the mean squared error. S represents the cumulative distance between the data and the fitted regression line. Thus, a lower value of S indicates better prediction of the response from the fitted regression equation. R^2 is a function of S that is scaled to be between 0 and 1. Thus, R^2 measures the proportion of variation in the response that is accounted for by the predictor variables. A higher R^2 indicates a better fit of the model to the data.

Adjusted R^2 also describes the variation of the response variable due to the relationship between the response variable and one or more predictor variables. The relationship is adjusted based upon the number of predictors in the model. R^2 values will always increase when a new predictor is added to the model. However, adjusted R^2 has an adjustment that prevents the model from appearing better simply due to adding marginally important predictor terms.

It is well known that the prediction ability of the model as measured by the previous criteria can provide an overly optimistic measure of the true forecasting performance (Garen 1992). In order to achieve closer representation of forecasting ability, cross validation procedures are recommended. Cross validation creates a validation series by dropping observations corresponding to the years, creating a regression equation for the remaining observations, and then predicting values for those years that were dropped. The PRESS (prediction sum of squares) statistic is such a measure of the predictive ability of the model. PRESS is based upon a leave-one-out cross-validation in which a single year or observation is removed when fitting the model. As a result, the prediction errors are independent of the predicted value at the removed observation (Garen 1992). For selecting a model when the primary interest is in prediction (forecasting), the model with the smaller PRESS is preferable (Montgomery et al. 2006). The PRESS value is also used to calculate the predicted R^2 statistic, which is a "R^2-like" statistic that reflects the prediction capability of the model (Myers 1990). Thus, predicted R^2 ranges from 0 to 1.0. PRESS is on the same scale as the residual sum of squares (squared units).

Another method to measure forecast skill is the linear error in probability (LEPS) score (Ward and Folland 1991; Potts et al. 1996). The LEPS score was originally developed to assess the position of the forecast and the position of the observed values in the cumulative probability distribution. Potts et al. (1996) describe the advantages of the LEPS score over traditional skill measurements such as root-mean-square error. The LEPS score (S'') and the average skill (SK) are defined in Tootle et al. 2007. A LEPS SK score of greater than +10% is generally considered "good skill". The LEPS SK score has been previously utilized as a measure of skill in streamflow forecast models (Piechota et al. 1998; Piechota and Dracup 1999; Tootle and Piechota 2004).

Statistics are also calculated to check for violation of model assumptions. These include autocorrelation and heterogeneity of variance. The Durbin-Watson statistic is used to check for autocorrelation in residuals. If adjacent observations are correlated (autocorrelation), the regression model will underestimate the standard error of the coefficients. As a result of underestimation, predictors may seem to be more significant than they actually are (Minitab Inc. 2007). To test for positive autocorrelation, the Durbin-Watson statistic (d) is compared to lower (dL) and upper (dU) critical values. If $d < dL$, there is statistical evidence that the error terms are positively autocorrelated. If $d > dU$, there is statistical evidence that the error terms are not positively autocorrelated, and if $dL < d < dU$, the test is inconclusive. Recall, that since the regression model is created using principle components, there are no issues with multicollinearity.

An important assumption of the regression model is that the residual error variance is equal or homogeneous across the observations. This assumption can be checked using a test developed by White (1980). This test evaluates whether or not the variance and the mean of the regression model are correctly specified. Under this hypothesis, the test statistic has a particular chi-square distribution from which the p-value (p_c) can be calculated.

RESULTS

Limited Record

A comparison is made between current NRCS methods and current NRCS methods incorporating ASM as a predictor for the limited period of record. In this study, the forecasted period of record (limited) used by the NRCS for USGS streamflow station 06620000 is 1979-2005 (27 years) while 1983-2005 (23) years is the period of record for USGS 06625000. Table 1.1 shows the numerical measures of skill. A slight increase in skill is achieved for both streamflow stations when incorporating ASM across all of these measures. For example, the R^2 value for USGS streamflow station 06620000 increases from 0.82 to 0.83 after incorporating ASM. USGS streamflow station 06625000 R^2 values are 0.79 using current NRCS methods, and 0.82 after ASM is added as a predictor. The LEPS SK scores for USGS 06620000 are 70.2 without soil moisture and 71.0 incorporating soil moisture. LEPS SK scores are 65.4 (without ASM) and 67.6 (with ASM) for USGS 06625000. While the authors acknowledge the increase in skill is minimal, the decrease in PRESS argues for the incorporation of soil moisture into the model for each station (Table 1.1). Table 1.1 also shows the Durbin-Watson statistic and the heterogeneity of variance test. These statistics are within acceptable ranges. In addition, USGS streamflow station 06625000 has a much higher PRESS value compared to USGS 06620000 for both periods of record. This is attributed to recorded flow at USGS 06620000 being much greater than at USGS 06625000. This is also evident in the standard error of the regression (S).

Extended Record

Identifying Predictors

By extending the period of record, adequate data is available to create the expert system. Of the nine SWE stations within the North Platte River Basin, four were selected based on the "rules" established in the Methods section. One station selected, Deadman Hill, is missing SWE data for 1969. Therefore the value is interpolated using the two closest SWE stations (Roach & Lake Irene). The correlation coefficient between precipitation (October to March) at Steamboat Springs and streamflow (AMJJ volume) for stations 06620000 and 06625000 are 0.75 and 0.76 respectively and they both show stability throughout the extended period of record. This shows that the precipitation records from Steamboat Springs are adequate and will be used in the study. Based on correlation values, and current NRCS methodologies, streamflow persistence is used as a predictor for USGS 06620000, but not as a predictor for USGS 06625000. As mentioned earlier, streamflow data was first recorded in this region in the early 1940's. For USGS streamflow station 06620000, the forecasted period is 1940-2005 (66 years) while 1941-2005 (65 years) is the forecasted period used for USGS station 06625000.

Comparison of Current NRCS Methods with and without ASM

A comparison is made between current NRCS methods and, current NRCS methods incorporating ASM as a predictor for the extended period of record. Table 1.2 shows the numerical measures of skill. By extending the period of record, increased hydrologic variability is incorporated. This variability produces a decrease in overall forecast skill when compared to the limited record. However, by extending the period of record, an expert (decision) system can be developed. For both streamflow stations, there is increase in forecast skill when incorporating soil moisture. For USGS 06620000, an increase from $R^2 = 0.67$ to $R^2 = 0.69$ is achieved after including ASM as a predictor. R^2 values for USGS 06625000 are 0.73 using current forecasting methods and 0.77 after incorporating ASM. The LEPS SK scores for USGS 06620000 are 63.5 without soil moisture and 64.6 incorporating ASM. LEPS SK scores are 66.0 (without ASM) and 66.9 (with ASM) for USGS 06625000. While the authors acknowledge the increases in skill are small, all forecasts produce a higher R^2, predicted R^2, adjusted R^2, and LEPS SK values when incorporating ASM. More importantly, the decrease in PRESS values show that the models incorporating ASM are preferable. Finally, it is important to note that the ASM data used in this research is modeled data that represents an entire climate division (i.e., large spatial area). The author's acknowledge this ASM data is most likely a poor reflection of upper watershed soil moisture, but, this is the best available data (for the extended period of record) in the region. The collection of soil moisture data, from improved land-based equipment or satellites, spatially upstream from the streamflow station(s) will most likely result in even greater improvement in overall model skill. Table 1.2 also shows the Durbin-Watson statistic and the heterogeneity of variance test. The Durbin-Watson statistic for USGS 06625000 (without ASM) is less than the value of dL. This test provides evidence of serial correlation that is accounted for when including ASM.

Expert System Incorporating ASM

ASM is used in an expert system in which three individual forecasts are developed for wet, dry and normal conditions. The number of years for each category are as follows: USGS streamflow station 06620000 (7 dry years, 50 normal years, 9 wet years); USGS streamflow station 06625000 (7 dry years, 49 normal years, 9 wet years). The expert system produces slight to moderate increase in overall skill when compared to the extended period of record forecast (with and without ASM) for both USGS streamflow stations. For example, the expert system results in an R^2 value of 0.73 for USGS 06620000, an increase from 0.67 when forecasting the extended period of record without ASM (i.e., current NRCS methodologies), and an increase from 0.69 when compared to incorporating ASM into the extended period of record. For USGS 0625000, the expert system completes the forecast with an R^2 value of 0.81. This skill is greater than forecasting the extended period of record without soil moisture (R^2 of 0.73) and forecasting the extended period of record with ASM (R^2 of 0.77). As displayed, the expert system results in improved skill when compared to applying NRCS methods (with and without incorporating ASM). Most notably, when current NRCS methods (e.g., without ASM) are compared to expert system results, further (e.g., R^2 increased from 0.67 to 0.73 and 0.73 to 0.81, respectively) improvement in skill is observed. Expert system LEPS SK scores are 64.5 and 70.2 for USGS 06620000 and USGS 06625000, respectively. See Figures 1.2a and 1.2b for a graph showing extended forecasts [without (w/o) ASM and Expert System] plotted versus the streamflow gauge (observed) value.

Improving Poor Forecasts

As previously mentioned, the NRCS has sought improvement in the modeling strategy that will increase the overall skill of the model while specifically providing better prediction of poor forecasts, or those years in which the model provided extremely poor prediction. Poor forecasting is defined in the Methods section. Slight to moderate increase in the measures of overall skill have been previously demonstrated. A “poor” forecast is determined by ranking (worst to best) each year and selecting the upper quartile (25%) of worst forecasts and defining them as “poor” forecasts. These poor forecasts are examined for both the limited and extended periods of record for both stations. Incorporating ASM resulted in a more accurate forecast for six out of the eight worst years for USGS 06620000 (Figure 1.3a), and four out of the six years for USGS 06625000 (Figure 1.3b) when forecasting the limited period of record. An average increase in forecast accuracy of 16% is achieved over these six years for USGS 06620000 when incorporating ASM. Over the 4 years in which including ASM into the model resulted in a better forecast for USGS 06625000, the average increase in forecast accuracy is 10%. For the extended record, incorporating ASM using the expert system approach resulted in a more accurate forecast for 14 out of the 16 poorest forecasted years for both USGS streamflow stations (Figures 1.4a and 1.4b) when compared to the forecast that did not include ASM as a predictor. An average increase in forecast accuracy of 23% is achieved for these 14 years when incorporating ASM for USGS 06620000, and 28% for USGS 06625000. Only six out of the 16 “poor” forecast years are considered extreme (wet or dry) for USGS 06620000 and only five of 16 are extreme based on ASM conditions for USGS 06625000. Therefore, since the majority of NRCS poor forecast years are considered to be normal based on the expert system approach, the process of removing extreme years (both dry and wet) results in improving “normal year” forecast accuracy.

CONCLUSIONS AND FUTURE WORK

The incorporation of ASM into NRCS streamflow forecasting models in the North Platte River Basin achieved both goals set forth by the NRCS. First, overall model skill is improved.

While the author's acknowledge the increase in overall model skill is slight, nevertheless, the decreased value of the PRESS statistic (in all cases) shows statistically that the model that incorporates ASM is the preferred model for forecasting. Second, a notable improvement is observed when attempting to improve "poor" forecasts. The limited period of record resulted in 10 out of 14 "poor" forecasts being improved while the extended period of record resulted in 28 out of 32 "poor" forecasts being improved. The development of an expert (decision) system, based on ASM, is a novel approach that reveals the importance of ASM in streamflow forecasting. While this research provides a basis to consider ASM in streamflow forecasting, there is a considerable void in soil moisture data availability, both in the length of record and the accuracy/precision of the data. Enhanced SNOTEL stations in the North Platte River Basin, that measure soil moisture digitally and in real-time, may result in further increased forecast skill when incorporated as predictors. Inexpensive instrumentation such as conductivity devices and tensiometers can also provide soil moisture data. For both calibrated conductivity-based devices and well-maintained tensiometers, the user can expect measurement accuracies of up to 90 to 95 percent (Murphy 1996). Further research may also incorporate NASA MODIS snow cover data in addition to SNOTEL data. MODIS data will reflect a spatial coverage of snowpack in the basin versus current (SNOTEL) point data. However, one limitation of using MODIS technology includes limited availability of data and digital images. With the increased importance of producing accurate streamflow forecasts, more soil moisture models (and arguably more accurate) are being created. Incorporating this soil moisture data from various available models and instrumentation may prove to be an important predictor in future streamflow forecasts.

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TABLE AND FIGURE CAPTIONS

Table 1.1: Statistics for the limited period of record.

Table 1.2: Statistics for the extended period of record.

Figure 1.1: Location map of Wyoming North Platte River Basin showing used predictors.

Figure 1.2: (a) Extended period of record forecasts (Q gage vs. Q w/o ASM vs. Q Expert) for USGS 06620000.
(b) Extended period of record forecasts (Q gage vs. Q w/o ASM vs. Q Expert) for USGS 06625000.

Figure 1.3: (a) Plot comparing forecasts for the worst quartile of "poor" forecasts using current forecasting methods (NRCS) with proposed methods (incorporating ASM) for USGS 06620000 limited period of record.
(b) Plot comparing forecasts for the worst quartile of "poor" forecasts using current forecasting methods (NRCS) with proposed methods (incorporating ASM) for USGS 06625000 limited period of record.

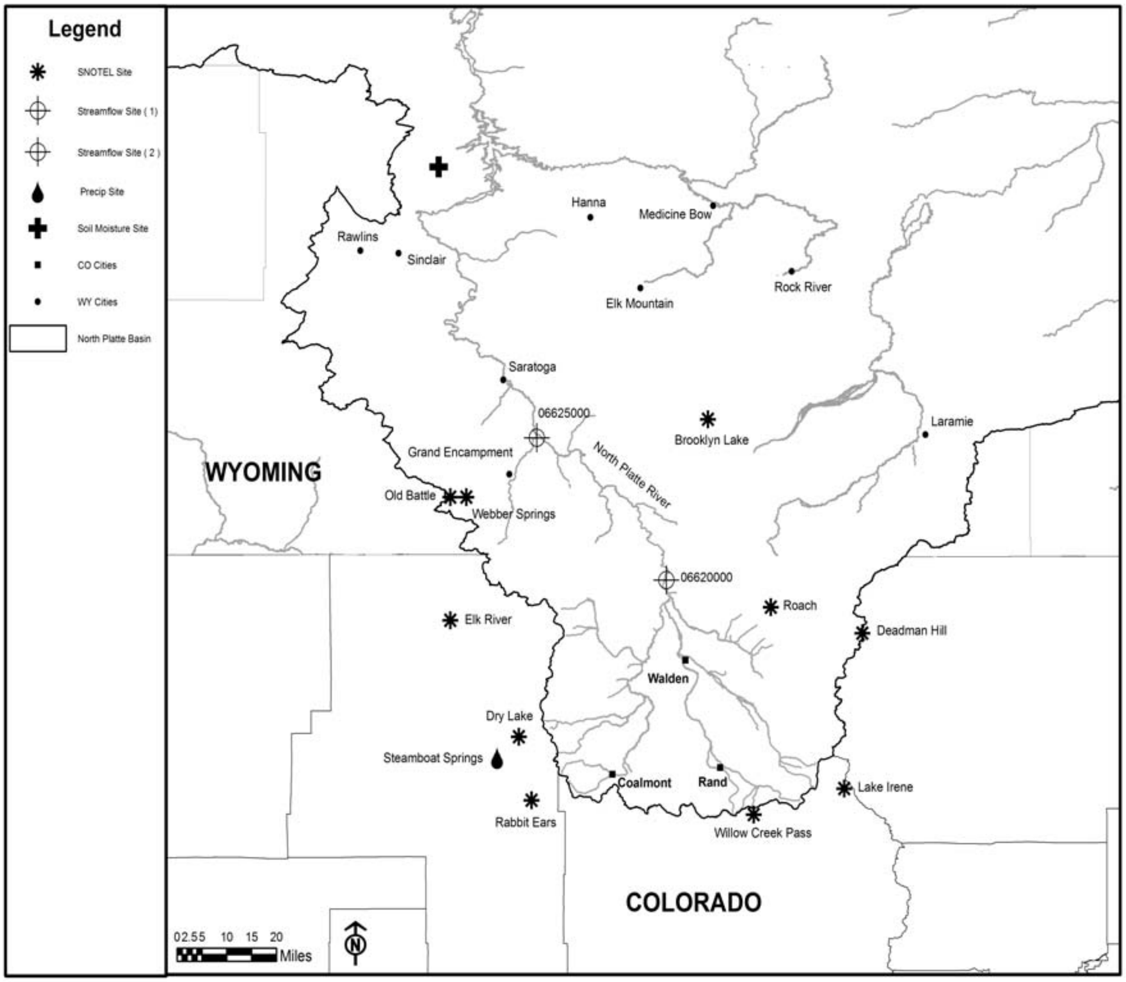
Figure 1.4: (a) Plot comparing forecasts for the worst quartile of "poor" forecasts using current forecasting methods (NRCS) with proposed methods (expert system) for USGS 06620000 extended period of record.
(b) Plot comparing forecasts for the worst quartile of "poor" forecasts using current forecasting methods (NRCS) with proposed methods (expert system) for USGS 06625000 extended period of record.

Table 1.1

	USGS 06620000 w/o ASM	USGS 06620000 w/ASM	USGS 06625000 w/o ASM	USGS 06625000 w/ASM
Period of Record	1979-2005 (27)	1979-2005 (27)	1983-2005 (23)	1983-2005 (23)
R^2	0.82	0.83	0.79	0.82
R^2(adj)	0.81	0.82	0.78	0.81
R^2(pred)	0.79	0.81	0.76	0.80
PRESS	90,535.17	87,107.75	17,429.70	14,800.00
S	56.80	55.30	26.81	24.83
Durbin-Watson	2.12	2.42	1.63	1.97
dL	1.24	1.24	1.26	1.26
dU	1.56	1.56	1.44	1.44
S""	18.96	19.2	15.04	15.54
SK	70.24	71.03	65.40	67.57
c_0	4.58	4.18	1.46	1.69
p_c	0.47	0.52	0.48	0.43

Table 1.2

	USGS 06620000 w/o ASM	USGS 06620000 w/ASM	USGS 06625000 w/o ASM	USGS 06625000 w/ASM
Period of Record	1940-2005 (66)	1940-2005 (66)	1941-2005 (65)	1941-2005 (65)
R^2	0.67	0.69	0.73	0.77
R^2(adj)	0.67	0.69	0.72	0.76
R^2(pred)	0.65	0.67	0.70	0.74
PRESS	286,191.85	269,145.60	48,715.10	42,312.50
S	65.00	63.00	26.50	24.60
Durbin-Watson	1.90	2.07	1.28	1.73
dL	1.57	1.57	1.53	1.50
dU	1.63	1.63	1.66	1.70
S""	18.96	19.18	42.83	43.47
SK	70.24	71.03	65.90	66.88
c_0	0.56	0.67	8.93	11.51
p_c	0.76	0.72	0.11	0.24


Legend
SNOTEL Site
Streamflow Site (1)
Streamflow Site (2)
Precip Site
Soil Moisture Site
CO Cities
WY Cities
North Platte Basin
Hanna
Medicine Bow
Rawlins
Sinclair
Elk Mountain
Rock River
Saratoga
06625000
Brooklyn Lake
Laramie
Grand Encampment
North Platte River
WYOMING
Old Battle
Webber Springs
06620000
Roach
Elk River
Deadman Hill
Walden
Dry Lake
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0 2.5 5 10 15 20
Miles
N

Figure 1.1

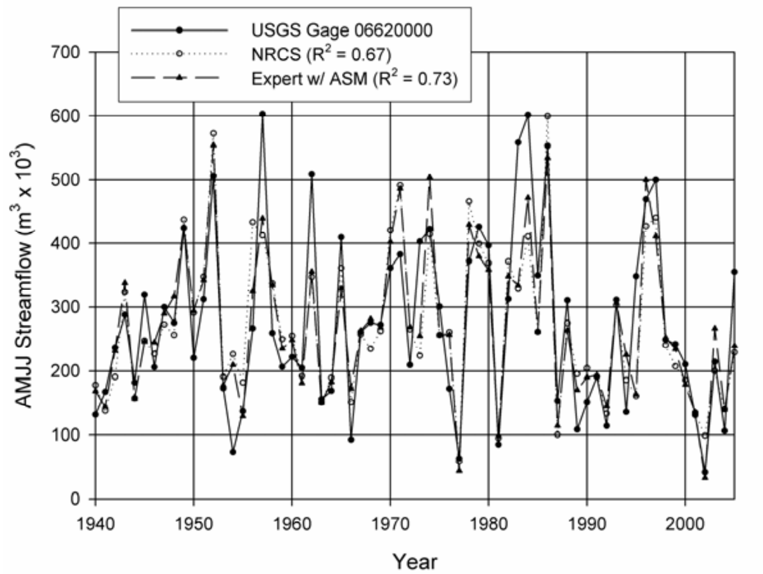

Figure 1.2(a)

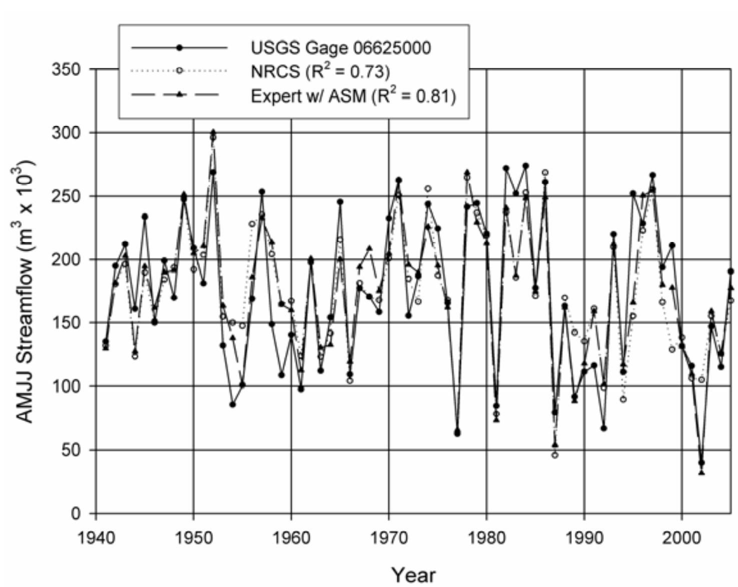

Figure 1.2(b)

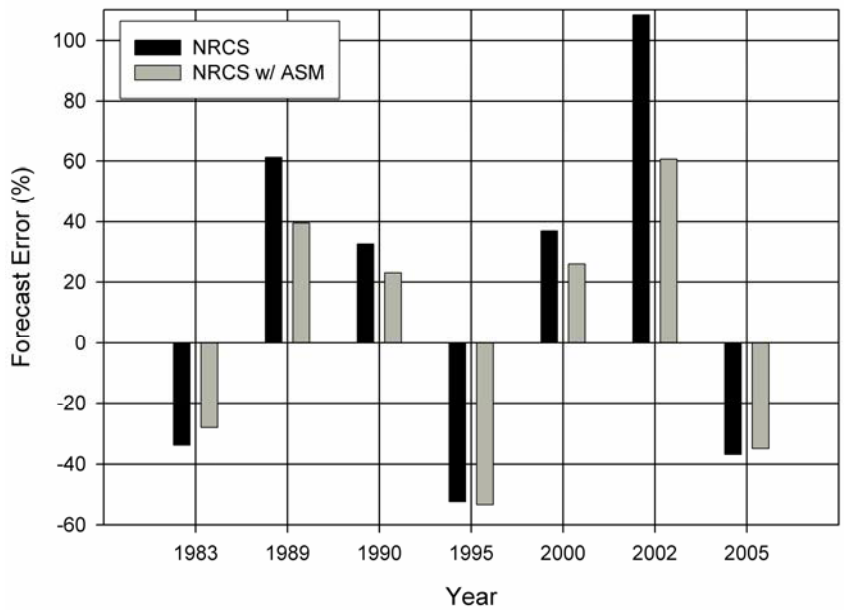

Figure 1.3(a)

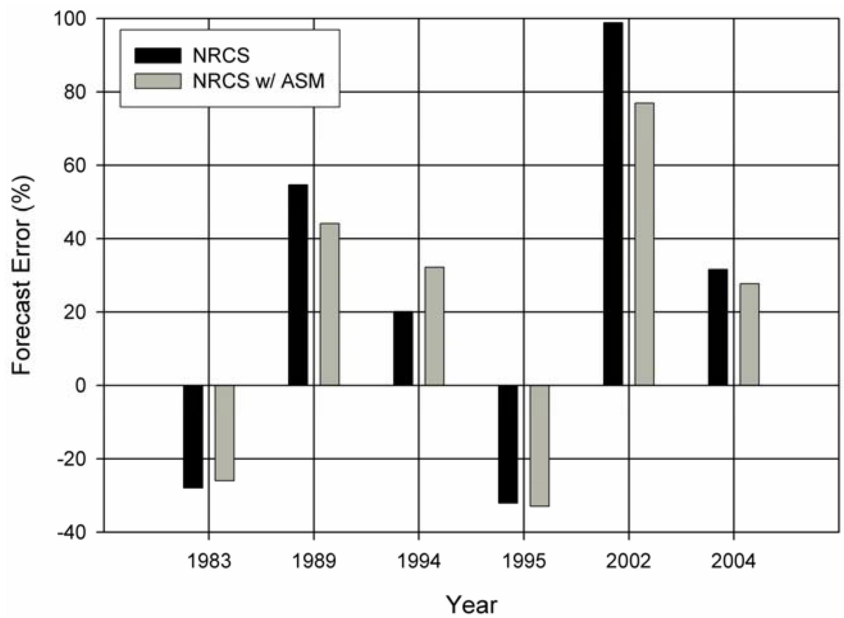

Figure 1.3(b)

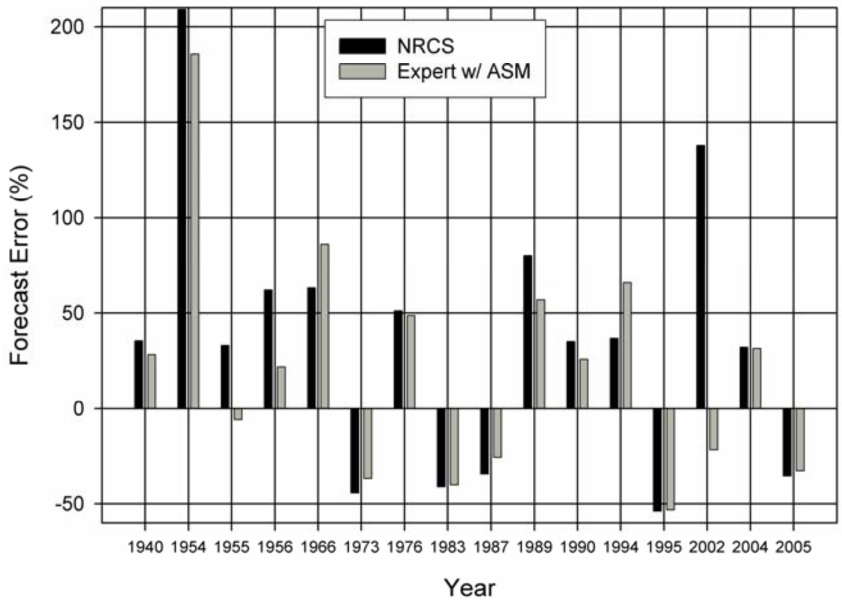

Figure 1.4(a)

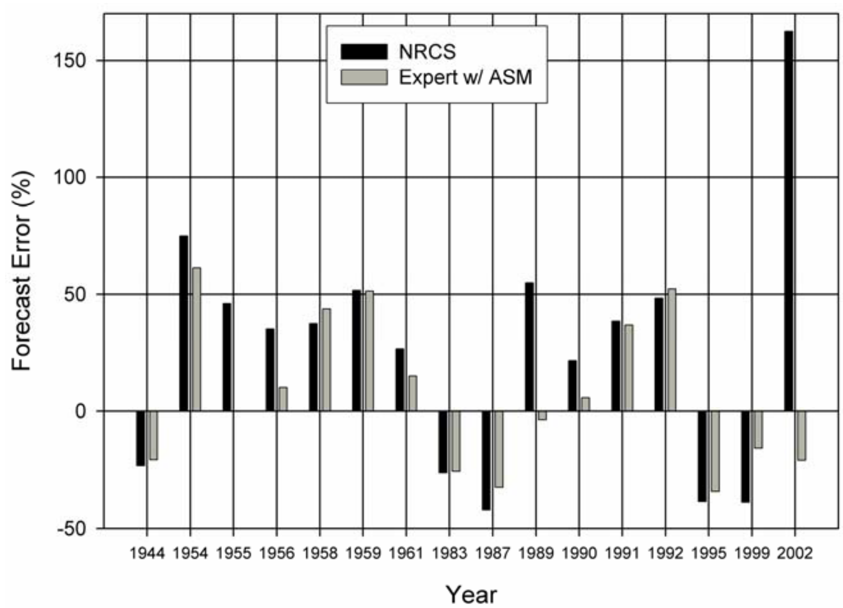

Figure 1.4(b)

CHAPTER 2 - Long Lead-time Streamflow Forecasting of the North Platte River Incorporating Oceanic-Atmospheric Climate Variability

ABSTRACT

An evaluation of the influence of oceanic-atmospheric climate variability on streamflow in the upper North Platte River basin is presented. Through the application of Singular Value Decomposition (SVD) statistical methods, sea surface temperatures (SSTs), 500 mbar geopotential height (Z_{500}) values and North Platte streamflow were evaluated over a historical period from 1948 to 2006. This resulted in the identification of new regions of highly correlated SSTs and Z_{500} that may not be represented by existing index regions (Niño 3.4 —defined El Nino Southern Oscillation region, PDO--Pacific Decadal Oscillation, and AMO—Atlantic Multidecadal Oscillation). A long lead-time approach was utilized such that a three month lead-time (seasonal average of monthly SSTs or Z_{500} for October, November and December) as well as a six month lead-time (seasonal average of monthly SSTs or Z_{500} for July, August and September) of previous year variability were used as predictors for the following year spring streamflow (seasonal monthly average of April, May, June and July). Temporal expansion series from SVD were utilized as predictors in a non-parametric model to develop continuous exceedance probability forecasts. The results displayed good skill using SSTs for the six month lead-time forecast and excellent skill using Z_{500} values for the three month lead-time forecast. The improved skill found over basic climatology forecasts will be useful to water managers when trying to predict and manage expected streamflow volumes several months in advance.

INTRODUCTION

Over the past several decades, hydrologists and climatologists have developed relationships between large scale oceanic-atmospheric variability and climate (hydroclimatology). Atmospheric – oceanic climatic and sea surface temperature (SST) variability can provide important predictive information about hydrologic variability in regions around the world. Significant research has focused on identifying atmospheric – oceanic climatic phenomena such as the El Niño-Southern Oscillation (ENSO) [Philander, 1990], the Pacific Decadal Oscillation (PDO) [Mantua, et al., 1997] and the Atlantic Multidecadal Oscillation (AMO) [Enfield et al., 2001]. Further research has identified what influence these phenomena have on U.S. hydrology, including streamflow and snowpack [e.g., Cayan and Peterson, 1989; Cayan and Webb, 1992; Kahya and Dracup, 1993, 1994a and 1994b; Enfield et al., 2001; Rogers and Coleman, 2003; Maurer et al., 2004; McCabe et al., 2004; Tootle et al, 2005, Hunter et al., 2006]. The relationships between atmospheric – oceanic climate variability may result in their utilization as long lead-time (e.g., three to six months) predictors (forecasters) of various hydrologic responses, including streamflow.

Streamflow forecasting is the process of predicting the volume of water at a specific location for a specific time period. Currently, the Natural Resources Conservation Service (NRCS) and the National Weather Service (NWS) cooperate to generate forecasts around the first of each month between January and June. Nearly all of these forecasts are produced using parametric statistical approaches such as multiple linear regression models [NRCS, 2007]. An alternative to typical parametric regression techniques is a non-parametric approach

Non-parametric routines avoid the usual assumption that the data comes from a normal distribution (or any specific distribution). Essentially, a non-parametric model is derived from the data and does not pre-define the form (i.e. linear or non-linear) of the function. Non-parametric methods have been successfully applied to streamflow forecasting. Lall [1995] performed an extensive analysis of applications of non-parametric probability uses in stochastic hydrology. Several other non-parametric methods (K nearest neighbor local polynomials and local weighted polynomials) have been successfully applied to hydrologic (and streamflow) forecasting [Lall and Sharma, 1996, Rajagopalan and Lall, 1999, Souza and Lall, 2003]. Piechota and Dracup [1999] applied non-parametric (kernel density estimator) methods to forecasting streamflow for long lead-times and showed significant improvement when comparing the results to the climatology (no skill) forecast [Piechota and Dracup, 1999]. The non-parametric kernel density estimator was also successfully applied to El Niño-Southern Oscillation (ENSO) affected streams in eastern Australia and Florida [Piechota et al., 1998, Tootle and Piechota, 2004]. The exceedance probability forecast developed provides an example of applying non-parametric techniques to forecasting. An exceedance probability forecast explains the likelihood that a certain streamflow volume will be equaled or exceeded during a certain period of time. Exceedance probability forecasts are used for the design and operation of water resource systems that require a high degree of system reliability [Piechota et al., 2001]. However, whether applying parametric or non-parametric techniques (utilizing climate variability), it is vital to identify statistically strong relationships (predictors) between climate variability and streamflow response.

Several methods are typically used to determine the relationship between two spatial-temporal arrays of data such as climate variability (e.g., SSTs) and streamflow. Common methods include correlation analysis, principal component analysis and singular value decomposition (SVD). Bretherton et al. [1992] evaluated several statistical methods and concluded SVD was simple to perform and preferable for general use. In a study between wintertime sea surface temperature and 500 mbar height (Z_{500}) anomalies, Wallace et al. [1992] determined that SVD isolates the most important modes of variability as well as discovering a coupling between the interannual variability of SST and Z_{500} due to their common link with global wave patterns. SVD has been used to identify relationships between oceanic SST variability and hydrologic variability. Wang and Ting [2000] evaluated Pacific Ocean SSTs and continental U.S. precipitation for concurrent (overlapping) time periods and identified simultaneous patterns of SST influence on precipitation. Uvo et al. [1998] applied SVD to evaluate Pacific and Atlantic Ocean SSTs (independently) and northeast Brazilian precipitation utilizing both a simultaneous and lagged approach. Rajagopalan et al. [2000] utilized SVD and applied a lag approach to evaluate global SST impacts on continental U.S. drought. Shabbar and Skinner [2004] applied SVD and utilized a lag approach in which winter global SSTs and summer Canadian drought [e.g., Palmer Drought Severity Index (PDSI) values] were evaluated and determined each mode representing a distinct oceanic / atmospheric phenomena (e.g., 1st mode – AMO, 2nd mode – ENSO, 3rd mode – PDO). Tootle and Piechota [2006] analyzed Pacific and Atlantic Ocean SSTs which resulted in the identification of several SST regions associated with streamflow regions in the continental United States. Tootle et al. [2008] applied this approach (SVD) to Pacific and Atlantic SSTs and Colombia streamflow, identifying several SST and streamflow regions of significance.

When examining the impacts of oceanic-atmospheric climate variability, a significant influence on that variability comes from various dynamics at different pressure levels in the atmosphere. In order to reference the height of the various pressure regimes, the term geopotential height is used. In essence, geopotential height is the height to the pressure zone of interest, as measured above the mean sea surface elevation. Blackmon [1976] did a study of the 500 mbar geopotential height (Z_{500}) of the northern hemisphere which presented long term averages of atmospheric parameters. Through a comparison, described in the study, interannual variability can be obtained and would allow for a comparison of various data sets and thus generate a circulation model that has the ability to replicate the atmosphere's behavior in low to mid frequency domains and in various spatial scales. Building upon the 1976 study, Blackmon [1977] explored the behavior of the 500 mbar wind statistics upon northern hemisphere wintertime circulation. The results of these studies suggested that Z_{500} index values can be attributed to substantial impacts on climate. On a global level Xoplaki et al. [2000] determined that the link between precipitation over Greece and changes in large scale atmospheric circulation are strong, specifically in relation to 500 mbar geopotential heights. As related to the work of this paper, Serreze et al. [1998] evaluated the relationship between snowfall and low frequency atmospheric variability and found that the troughs and ridges associated with the 500 mbar zone do play a role in the characteristics of snowfall over the eastern United States. Grantz et al. [2005] explored the impacts of including Z_{500} height index values as predictors in streamflow forecasting models and discovered an improved skill with such an addition.

The North Platte River (Figure 2.1) originates in north central Colorado with tributaries and contributing basins predominately located in mountainous regions of Colorado and Wyoming. As a result, most of the annual streamflow can be attributed to melting snowpack that has accumulated during the winter and early spring months in the mountainous headwater regions. The North Platte River flows north into Wyoming, then east to Nebraska. Present and future use of water resources in the North Platte River Basin (NPRB) are heavily regulated and controlled by the Supreme Court Decree for the North Platte River [North Platte River Basin Overview, 2008]. Recent lawsuits regarding interstate water allocations have augmented the need for a more skillful and longer lead-time forecast. Currently, only parametric (regression) models are used to develop a relationship between predictor variables (precipitation, snow water equivalent, antecedent streamflow, etc.) and the predictand (April-May-June-July streamflow volume). From a forecasting perspective, the challenge with the NPRB is the lack of a distinct climate signal (e.g. ENSO, PDO, AMO) per research performed on unimpaired streamflow and snowpack in the continental and western U.S. [Tootle et al., 2005; Hunter et al., 2006]

The proposed research will develop a unique long lead-time (three to six months) streamflow forecast of unimpaired streamflow stations in the NPRB utilizing oceanic-atmospheric climate information. Similar to Grantz et al. [2005], Pacific and Atlantic Ocean SST variability and Z_{500} index values will be utilized as predictors. However, in lieu of using correlation to identify predictors, SVD techniques will be applied to identify spatial regions of SSTs and Z_{500} that relate to streamflow variability in the NPRB. Additionally, a non-parametric approach will be utilized to develop an exceedance probability streamflow forecast comparable to the work of Piechota et al. [2001].

DATA

Streamflow Data

Data from four unimpaired streamflow stations (Q1 - #06620000, Q2 - #06625000, Q3 - #06630000 and Q4 - #06635000) in the Upper North Platte River Basin (Figure 2.1) were obtained from the U.S. Geological Survey (USGS) National Water Information System [USGS, 2008]. USGS provides historical monthly mean streamflow in cubic feet per second (cfs). The average monthly streamflow rate in cfs for April, May, June and July (AMJJ) were summed and converted into streamflow volumes using appropriate conversions. The period of streamflow volume used in the analysis was 1949 to 2006 (57 years).

Climatic Indices

Three of the applicable predefined datasets representing oceanic – atmospheric climatic phenomena are the Niño 3.4 index, the PDO index and the AMO index. The average monthly values for the climatic indices (Niño 3.4, PDO and AMO) were averaged for the six month lead-time period of July, August and September [JAS(-1)] as well as for the three month lead-time period of October, November and December [OND(-1)]. The (-1) nomenclature identifies that the predictor periods are for the previous year to the predictand, AMJJ streamflow. The time span averaged was 1948 to 2005 (57 years) and preceded the streamflow volumes used by one year.

The Niño 3.4 [Trenberth, 1997] SST region is located along the equatorial Pacific Ocean (5P^{oP}S – 5P^{oP}N, 170P^{oP} – 120P^{oP}W) and monthly index data were obtained from the NOAA ESRL Physical Sciences Division [http://www.cdc.noaa.gov/Pressure/Timeseries/Nino34/]. The Niño 3.4 index was used since it is an overall representation of ENSO. The PDO is a oceanic / atmospheric phenomena associated with persistent, bimodal climate patterns in the northern Pacific Ocean (poleward of 20P^{oP} north) that oscillate with a characteristic period on the order of 50 years (a particular phase of the PDO will typically persist for about 25 years) [Mantua, et al., 1997; Mantua and Hare, 2002]. PDO Index [Mantua et al., 1997, Hare and Mantua, 2000] values were obtained from the Joint Institute for the Study of the Atmosphere and Ocean, University of Washington [http://tao.atmos.washington. edu/pdo/]. The Atlantic Multidecadal Oscillation (AMO) index was introduced by Enfield et al. [2001] as a simple basin average of North Atlantic Ocean (0 to 70P^{oP}) sea surface temperatures (SSTs). The AMO index consists of detrended (dividing, centering and re-scaling the data to account for unimodal data sets) SST anomalies for the previously defined Atlantic Ocean region. AMO index values are available from the National Oceanic and Atmospheric Administration (NOAA) ESRL Physical Sciences Division [http://www.cdc.noaa.gov/Pressure/Timeseries/].

Pacific and Atlantic Ocean Sea Surface Temperature Data

SST data for the Pacific and Atlantic Oceans were obtained from the National Climatic Data Center [http://www.cdc.noaa.gov/cdc/data.noaa.ersst.html]. The oceanic SST data consists of average monthly values for a 2^{o} by 2^{o} grid cell [Smith and Reynolds, 2004]. The extended reconstructed global SSTs were based on the Comprehensive Ocean-Atmosphere Data Set (COADS) from 1854 to present [Smith and Reynolds, 2003].

The overall gridded data region of Pacific Ocean SST data used for the analysis was longitude 100°E to longitude 80°W and latitude 30°S to latitude 60°N while the region of Atlantic Ocean SST data used for the analysis was longitude 80°W to longitude 20°W and latitude 30°S to latitude 60°N. The longitudinal boundaries of this study (100°E to 20°W) extended the regions of Grantz et al. [2005] (100°E to 60°W) to encompass the possibility of more Atlantic ocean influences while the latitudinal boundaries were identical. Similar regions were explored by Tootle and Piechota [2006] due to these regions representing the majority of oceanic—atmospheric climate influences on U.S. climate (i.e., storm tracks such as Pacific Ocean frontal storms). The regions selected were also similar to other studies, such as those of Wang and Ting [2000]. Similar to the climate indices, average monthly values were averaged for the predictor seasons [JAS(-1) and OND(-1)] for each SST cell.

500 mbar Geopotential Height Index Data (Z_{500})

The monthly Z_{500} index data are a product of the NCEP/NCAR Reanalysis 40-year Project [Kalnay et al., 1996] and can be obtained from the NOAA Physical Sciences Center [http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl]. The Z_{500} index data are given on a 2.5° x 2.5° latitude and longitude grid and are available from 1948 to 2008. The overall gridded data region of data used for the analysis was longitude 100°E to longitude 20°W and latitude 30°S to latitude 60°N, similar to the previously described SST regions. Like the SSTs, average monthly values were averaged for the predictor seasons [JAS(-1) and OND(-1)] for each Z_{500} cell.

METHODS

Climate/Streamflow Relationships

Comparable to Grantz et al. [2005], the first step was to analyze relationships between potential predictors and predictands. The relationship between ocean-atmospheric variability and streamflow was examined through the development of a correlation table. The correlation table was created using typical correlation techniques between the seasonal [JAS(-1) and OND(-1)] climate indices (Niño 3.4, PDO and AMO) and the four streamflow (AMJJ) stations (Q1, Q2, Q3, Q4).

Singular Value Decomposition (SVD)

Grantz et al. [2005] examined the relationships between streamflow and oceanic-atmospheric signals using visual inspection of correlation maps and composite analyses. The work presented here builds upon that methodology through the use of SVD. SVD is a powerful statistical tool for identifying coupled relationships between two, spatial-temporal fields. Bretherton et al. [1992] provides a detailed discussion of the theory of SVD, while Tootle et al. [2008] and Tootle and Piechota [2006] provide a brief description of SVD, as applied in the current research.

Initially, a matrix of standardized SST (or Z_{500}) anomalies and a matrix of standardized streamflow anomalies (for the four NPRB stations) were developed. The time dimension of each matrix (i.e., 57 years) must be equal while the spatial component (i.e., SST cells or Z_{500} and North Platte streamflow stations) can vary in dimension. The cross-covariance matrix was then computed for the two spatial, temporal matrices and SVD was applied to the cross-covariance matrix and physical information regarding the relationship between the two was obtained. The resulting SVD of the cross-covariance matrix created two matrices of singular vectors and one matrix of singular values. The singular values were ordered such that the first singular value (1st mode) was greater than the second singular value and so on. Bretherton et al. [1992] defines the squared covariance fraction (SCF) as a useful measurement for comparing the relative importance of modes in the decomposition. Each singular value was squared and divided by the sum of all the squared singular values to produce a fraction (or percentage) of squared covariance for each mode.

Finally, the two matrices of singular vectors were examined, generally referred to as the left (i.e., SST or Z_{500}) matrix and the right (i.e., streamflow) matrix. The first column of the left matrix (1st mode) was projected onto the standardized SST or Z_{500} anomalies matrix and the first column of the right matrix (1st mode) was projected onto the standardized streamflow anomalies matrix. This resulted in the 1st temporal expansion series of the left and right fields, respectively. The left heterogeneous correlation figure (for the 1st mode) was determined by correlating the SST or Z_{500} values of the left matrix with 1st temporal expansion series of the right field and the right heterogeneous correlation figure (for the 1st mode) was determined by correlating the streamflow values of the right matrix with the 1st temporal expansion series of the left field. The left temporal expansion series have a physical meaning since they represent SST or Z_{500} variability that may not already be included in existing SST indices and could represent a new index of SST variability. This may then be useful in forecasting streamflow for stations that have high correlations with the temporal expansion series. Utilizing an approach similar to Rajagopalan et al. [2000] and Uvo et al. [1998], heterogeneous correlation figures displaying 90% significant correlation values for SST and Z_{500} regions were reported. These reported correlations statistically differ from zero at a 10% significance level. A 10% significance level was selected to balance the need to identify correlations that differ from zero, while also recognizing that the relationships between SSTs and Z_{500} is subtle. As a result, correlations which are large in magnitude may not be detected at smaller significance level (e.g., 1%). While SVD is a powerful tool for the statistical analysis of two spatial, temporal fields, there exist several limitations to its use that should be investigated [Newman and Sardeshmukh, 1995]. Generally, if the leading (1st, 2nd, 3rd) modes explain a significant amount of the variance of the two fields, then SVD can be applied to determine the strength of the coupled variability present [Newman and Sardeshmukh, 1995]. However, when using SVD to examine two fields, the examiner must exhibit caution when attempting to explain the physical cause of the results [Newman and Sardeshmukh, 1995].

Forecast Methodology

The streamflow forecast developed is a continuous exceedance probability curve that can be used for any assumed risk level and was developed by Piechota et al., [2001]. The "no skill / climatology" forecast curve is generated by dividing the rank of each historical value by the total number of years in the record.

Two advantages are found using the model developed by Piechota et al. [2001]: it considers the continuous relationship between the predictand and the predictor, and it does not assume a particular model structure. It suffers, however, from its semi-empiricism; fitting the model to the data points assumes that the historical data represents the entire population. A detailed description of the methodology and model can be found in Piechota et al., [2001] and Piechota et al., [1998]. A brief description of the model (for one predictor) is provided below:

1. The climate predictor values (Pi) for each year and the corresponding streamflow predictand values (Qi) for each year are compiled, where (Pi) represents the temporal expansion series obtained from SVD, as described in the methods section, for SSTs or Z500 index values.
2. The streamflow values (Qi) are ranked in ascending order and the corresponding climate predictor (Pi) for the corresponding year of the streamflow are noted.
3. The first data point for analysis occurs immediately after the five lowest streamflow values (Qi) and the last point for analysis occurs immediately prior to the five highest streamflow values (Qi). This is required since a minimum of five values are needed to generate a probability density function.
4. The first data point for analysis is the sixth ranked streamflow value (lowest to highest) based on #3 above. Using the kernel density estimator (Silverman, 1986 and Piechota et al., 1998), a probability density function is developed for all climate predictor values below the first data point and a probability function is developed for all climate predictor values above the first data point. Whereas f(x) is the probability density function expressed as,

$$f(x) = \frac{1}{hn}\sum_{i=1}^{n}\left[k\left(\frac{x - x_i}{h}\right)\right]$$

$$h_i = .9A_i n_i^{-\left(\frac{1}{5}\right)}$$

$$A_i = \min\left(\sigma_i\ ,\ \frac{interquartile\ range}{1.34}\right)$$

where,

- X_1 to X_i is a set of n observations
- k( ) is the kernel function
- h is the bandwith
- optimal h = h_i
- σ_i is the stdev of predictor data in each subset i
- n_i is the # of observations in each subset.

and the Bayes probability theorem is expressed as,

$$Prob\left(\frac{Q_i}{x}\right) = \frac{P_i f_i(x)}{\sum_{i=1}^{k} P_i f_i(x)}$$

where,

- X = predictor value
- Q_i = streamflow
- P_i = prior probability streamflow
- f_i (x) = probability density function of prior X value

5. A unique probability value is determined for each predictor value, given the sixth ranked streamflow value. These values are single points on the exceedance probability curve (Probability versus Streamflow). The procedure is then repeated for the seventh ranked streamflow value and so on.

6. An exceedance probability is then determined for each predictor value. The forecast curve will represent the probability of exceeding a value of streamflow, based on the value of the predictor.

7. The final exceedance probability forecast is found by combining the three individual forecasts into one combination forecast that has better overall skill. The combination forecast is found by applying weights a, b, and, c to the three models so that the weights add up to one. The optimal forecast is found by applying more weight to individual forecasts that better predicts streamflow and less weight to poor individual forecasts. These optimal weights are determined by an optimization procedure that evaluates the Linear Error in Probability Space (LEPS) score for all possible combinations, using weighting increments of 0.02 in which the weights vary between 0 and 1 for each model. The final combination forecast is the model with the highest LEPS score.

The skill of the forecast, as produced by the model, was measured using the Linear Error in Probability Space (LEPS) score. The LEPS score is a measure of skill that was originally developed to assess the position of the forecast and the position of the observed values in the cumulative probability distribution (non-exceedance probability); the LEPS score can be used for continuous and categorical variables [Ward and Folland, 1991; Potts et al., 1996]. A modified LEPS score is required due to the absence of a convenient measure of skill for an exceedance probability forecast. A better measure of skill is one in which more weight is given to a forecast that effectively predicts low or high flow and less weight to a forecast that successfully predicts average flow. The application of the LEPS score is desirable here because it is less sensitive to changes near the center of the cumulative probability distribution and more sensitive to forecasts of high or low values. Essentially, it rewards a successful forecast of extreme values [Piechota et al., 2001]. The developmental steps and the equations used to generate a LEPS score for an exceedance probability forecast can be reviewed in Piechota et al. [2001] and a brief description is hereby provided. In terms of probability, the LEPS score measures the distance between the forecast and observed values. First, a "no skill" or "climatology" curve was developed for the observed yearly streamflow values. The "climatology" curve was created by ranking observed yearly streamflow values in decreasing order (i.e., exceedance probability) of magnitude and dividing the rank of each observed value by the total number of years in the record. The LEPS score is defined as

$$S'' = 3 * (1 - |Pf - Po| + Pf2 - Pf + Po2 - Po) - 1$$

where Pf and Po are the forecasted and observed cumulative probabilities, respectively. The LEPS score was calculated for each year and "good" or "bad" forecast years were identified. The average skill (SK) is defined as

$$SK = \frac{\sum 100S''}{\sum S''_m}$$

where the summation S" is for all years of record. If S" is positive, S"m is the sum of the best possible forecast (i.e. Pf = Po) for all years of record. If S" is negative, S"m is the sum of the worst possible forecast (i.e. Pf = 1 or 0) for all years of record. A LEPS SK score of greater than +10% is generally considered good skill.

The skill associated with each individual forecast is calculated for calibration and cross-validation analyses. The LEPS score for the calibration analysis does not provide an independent skill score because it is based on the same data in which the model was calibrated. To report the skill scores explained in the results section, each individual yearly calibrated and cross validated LEPS skill score was averaged over the entire 57 year period of record to develop an overall average forecast skill. Additionally, various combinations of different predictors (i.e. AMO, SST1, 500 mb1, Niño 3.4, SST1, 500mb1) were modeled in an attempt to obtain an optimal weight amongst the various predictors.

RESULTS

Climate Indices

As shown in Table 2.1, and as similarly reported by Grantz et al. [2005], the standard indices did not show significant relationships with spring streamflow volumes at any of the locations. Consequently, as described by Grantz et al. [2005], an investigation between large-scale oceanic-atmospheric variability and its link with streamflow was examined as a potential predictor.

When correlating the PDO index with the four previously defined streamflow stations (AMJJ volume) for both three and six month [JAS(-1)] lead-times, the correlation values resulted in no stations exceeding 90% significance. Similarly, the Niño 3.4 index resulted in none of the four stations exceeding 90% significance for either time period. The Niño 3.4 and PDO correlation coefficient values for both JAS(-1) and OND(-1) for Q1, Q2, Q3 and Q4 are close to 0 and therefore conclude that the Niño 3.4 and PDO signals are not prominent in the upper NPRB. When correlating the AMO index, all four stations exceeded 90% significance for the JAS(-1) (six month) lead-time period, whereas only one exceeded 90% significance for the three month lead-time. The AMO displays a stronger presence in the NPRB, as shown by its higher correlation coefficient values; however the coefficient values are not strong enough to form the basis for a skillful forecast. The correlation analysis was a preliminary study which verified the need to generate regions through the use of SVD that showed a significant relationship to the NPRB. Additionally, each predefined climate index was analyzed through the forecast model such that calibration and cross validation skill was reported. As explained by Tootle and Piechota [2004], calibration uses all of the data to calibrate the weights and then computes the skill based on all the data. Table 2.2 shows the weights (in percentage) applied by the cross validation model to each index. The calibration and cross validated skill score, also in percentage, are displayed immediately below the weights values. The weights displayed show that for JAS(-1), 100% of the weight to develop the cross validated exceedance probability forecast was applied to the AMO signal. The LEPS scores for the calibration analysis were greater than +10% for Q2 and Q4. However, cross-validation provides a more independent assessment of the forecast skill and of the weights applied to each model [Elsner and Schmertmann, 1994; Michaelsen, 1987]. Cross-validation allows the model to remove a year, calibrate the model, and then test the model on the year that was removed. This procedure is repeated for all years. The use of cross-validation eliminates spurious predictors and artificial skill. The LEPS score for the cross-validation analyses drops considerably when compared to the LEPS score for the calibration analysis. It can be reasoned that a good forecast would be indicated by a cross-validated LEPS score at or above +10%, which is not evident in any of the climate index results. The highest cross validated skill score for the JAS(-1) was the model run with Q4 and the AMO index, resulting in a value of 1.4%. The results of the OND(-1) run exhibit different behavior in terms of the weights being split amongst different signals. The Q1 run resulted in 33% of the forecast weight being placed on the Niño 3.4 signal. Different weights are selected by the model in an attempt and achieve the most skillful forecast. The weights selected by the model for each run are shown in Table 2.2. The calibration scores are all below +10% as well as all of the cross validated LEPS score values being negative, indicating the climate indices for the OND(-1) are poor predictors of streamflow volume in the NPRB.

Sea Surface Temperatures (SSTs)

When applying SVD to Pacific / Atlantic Ocean SSTs and North Platte streamflow, this resulted in squared covariance fractions (SCF) of 84.3% - 1st mode, 12.7% - 2nd mode and 1.7% - 3rd mode for the JAS(-1) lead-time period. The OND(-1) lead-time period resulted in SCFs of 81.2% - 1st mode, 15.3% - 2nd mode and 2.0% - 3rd mode. Therefore, for both lead-times, the 1st mode clearly identifies the strongest relationships. The total number of Pacific / Atlantic Ocean SST cells was 4329. For the 1st mode of JAS(-1) variability, 528 Pacific / Atlantic Ocean SST Cells (12.2%) were identified as significant. Figure 2.2 represents heterogeneous correlation maps (90% significance or $|r| > 0.21$) displaying significant Pacific / Atlantic Ocean SST for the 1st mode of SVD for the JAS(-1) lead-time. All four North Platte River streamflow stations were identified as being significant. For the 1st mode of OND(-1) variability, 493 Pacific / Atlantic Ocean SST Cells (11.4%) were identified as significant. Modes 2 and 3 were not reported based on the lack of significance of the SCF for both lead-times.

The results of the forecast model runs for JAS(-1) and OND(-1) are presented in Table 2.2. The table displays the temporal expansion series as row headings, for modes 1, 2 and 3 (SST1, SST2, SST3 respectively) of the SVD analysis, on the left. The weights applied to each temporal expansion series are displayed as a percentage, for the respective streamflow station (Q1, Q2, Q3 and Q4). The model applied 100% of the weight of the forecast on the first mode temporal expansion series (SST1). The 100% weighting acknowledges that the region defined through the SVD analysis for mode 1 has the strongest spatial-temporal relationship [84.3% -- JAS(-1) and 81.2% -- OND(-1)] and consequently is the best predictor for all four streamflow stations. The calibration and cross validated LEPS skill scores displayed in Table 2.2 are averages over the entire period of analysis (57 years). The six month lead-time [JAS(-1)] calibration LEPS skill scores are all above +10%. Even more appealing are the results of the JAS(-1) cross validated LEPS skill scores. Three of the four stations exhibit a cross-validated skill score near +10% with Q4 actually surpassing +10% with a value of +10.2%. For the three month lead-time forecast [OND(-1)], the calibrated skill scores were close to those of the six month lead-time scores. However, the cross-validated skill scores show a general decrease in skill value, with the most skillful result being +6.2% for Q2. It should be noted that for both lead-time periods, the cross validated skill for all analyses are above zero, indicating that the forecast model has better skill than the climatology forecast (skill = 0). Figure 2.3 presents examples of poor and good exceedance probability forecasts for individual years for each streamflow station for the JAS(-1) lead-time. For example, the 1963 Q2 vs. JAS SST represents a good forecast (cross validated

LEPS score of 61.17%). Using this graph, a water manager, assuming a 50% risk level (50% exceedance) would have correctly projected an average AMJJ streamflow volume of 1.12 x 10^8 cubic meters (m^3). Utilizing the climatology forecast at a 50% exceedance level, the water manager would have over-forecasted the projected supply at 1.75 x 10^8 m^3 .On the same note, there are risks associated with poor forecasts. Using the 1996 Q1 vs. JAS SST graph as an example of a poor forecast (cross validated LEPS score of -61.08%), a water manager assuming a 50% risk (50% exceedance) would have predicted a streamflow volume of 2.01 x 10^8 m^3 when in fact 4.69 x 10^8 m^3 was actually reported. Nevertheless, by averaging the entire period of record (57 years), for each streamflow station, the positive cross validated skill score is relatively close to +10%. This provides evidence for a greater number of good forecasts than poor forecasts.

500 mbar Geopotential Height Index

SVD analysis of 500 mbar Geopotential Height Index values and North Platte streamflow resulted in squared covariance fractions (SCF) of 70.3% - 1st mode, 24.1% - 2nd mode and 3.4% - 3rd mode for the JAS(-1) lead-time. SCFs for the OND(-1) lead-time were 73.4% - 1st mode, 22.0% - 2nd mode and 2.5% - 3rd mode. The 1st mode of variability (only) was reported, based on the significant squared covariance fraction reported for the 1st mode. The total number of Z_{500} Cells was 3589. For the 1st mode of variability and the JAS period, 94 Z_{500} Cells (2.6%) were identified as significant. For the 1st mode of variability and the OND(-1) period, 207 Z_{500} Cells (5.8%) were identified as significant. OND(-1) heterogeneous correlation maps (90% significance or $|r| > 0.21$) displaying significant Z_{500} regions and North Platte River streamflow stations for the 1P^{stP} mode of SVD are shown in Figure 2.4.

Table 2.2 displays the results of the model weights, calibration and cross validation skill scores, in the same format as described in the SST results section. Similar to the SST results, the temporal expansion series for mode 1 of Z_{500} turned out to be the predominant predictor driving the model. One hundred percent (100%) of the weight was applied to 500mb1 for both lead-times at all streamflow stations. Interestingly, we find that for both three and six month lead-times, the calibration skill values are all above +10% with substantial increase in skill for the three month OND(-1) lead-time. Likewise an improvement in cross validated skill is noticed for the OND(-1) lead-time over the JAS(-1) period. The cross-validated skill scores for the OND(-1) lead-time all exceed +10% whereas only one of the JAS(-1) skill scores exceed +5%. An explanation for these results will be examined in the discussion section. These results were similar to those of Grantz et al. [2005] in that an increase in skill was shown with decreasing lead-time when using the Z_{500} index as a predictor. Examples of poor and good exceedance probability forecasts utilizing Z_{500} are presented in Figure 2.5. Please refer to the discussion in the SST results section regarding the interpretation of poor and good exceedance probability forecast graphs.

DISCUSSION

The predefined climate index regions for the Niño 3.4, PDO and AMO lack the spatial-temporal relationship needed to produce skillful forecasts for the NPRB. In an attempt to find an ideal relationship, we expanded upon the methods of Grantz et al. [2005]. Through the use of a more powerful spatial-temporal analysis (SVD) we were able to locate “significant regions” of

SST and Z_{500} regions that tele-connected with the streamflow stations in the NPRB. The correlation values resulting from the SVD analysis, for each predictor, are displayed in Table 2.1. The SST "significant region" determined in this study was similar to that identified by Wang and Ting [2000], Tootle and Piechota [2006] and Grantz et al. [2005]. The unique aspect about the NPRB is that no significant SST regions were identified in the vicinity of the traditional ENSO belt (equatorial Pacific Ocean region). The predominant "significant region" identified for SSTs in this study was located approximately 20°W and 25° N of the Niño 3.4 region. Likewise, no significant regions were identified in the neighborhood of the typical PDO region. These findings verify the initial analysis which resulted in poor correlation values between the Nino 3.4, PDO and NPRB streamflow stations.

As a result of the stronger correlation values between NPRB streamflow stations and the AMO index in the preliminary analysis, the east longitudinal boundary was extended in an attempt to capture more Atlantic Ocean SST variability. The majority of the Atlantic Ocean SSTs displayed a significant relationship to NPRB streamflow (Figure 2.2), with a region off the coast of Africa displaying the highest significance. The region off the coast of Africa is similar to a region found in Tootle and Piechota [2006]. These findings reinforce the stronger correlation of the AMO index.

The significant region for Z_{500} (northwest/north central U.S.) was similar to the location found by Grantz et al. [2005]. There is a long history of the relationship between SSTs and streamflow forecasting but Grantz et al. [2005] and the work presented here examined the outcome of incorporating the 500 mbar geopotential height. Z_{500} is approximately 18,000 feet above sea level and has been linked to various climate processes. In mid-latitudes, Z_{500} transitions rapidly from large to low values across a circumpolar jet stream. A jet stream (fast flowing narrow currents of air) is located where the geopotential height contours are closest together (changing in height most rapidly). This jet stream consists of a series of transient troughs and ridges, which are the upper air counterparts of surface cyclones and anticyclones. The relatively shorter wave troughs in the jet stream are usually associated with surface cyclones and precipitation. Especially in winter, precipitation is strongly modulated by Z_{500}, and the deeper the short-wave trough or the stronger the jet, the more intense the surface cyclone and the heavier the precipitation. The precipitation is concentrated in frontal disturbances located just downstream of a Z_{500} trough. In the NPRB, most of that precipitation in winter falls as snow on the mountain ranges flanking the south and west sides of the upper NPRB. The general pattern of the polar jet stream over the United States in winter is such that it comes down from the coast of Alaska, just south of Anchorage, and then moves laterally from northwest to southeast across the northern tier of the continental United States. For regions that are typically equatorward of the jet, such as California and possibly also the upper NPRB, an anomalous southward excursion of the jet on average, over the course of a winter, should imply more trough passages and thus more precipitation. Places typically poleward of the jet, such as Fairbanks, Alaska, tend to be wetter when the jet is anomalously far north, i.e. when Z_{500} is anomalously high [B. Geerts, personal communication, 3/10/2008]. Grantz et al. [2005] explained that the Z_{500} and the wind vectors associated with the Z_{500} troughs and ridges drive winter precipitation over west central Nevada. These findings suggest that the winter weather in the west central U.S. is predominately driven by the location and magnitude of wind vectors (i.e., jet streams). Meteorological analyses examining the relationship between the jet stream, and pressure troughs and ridges suggest that precipitation responds immediately to Z_{500}. The jet stream and its wave train are very transient (e.g., a trough and its associated frontal precipitation may pass an area in less than a day). [B. Geerts, personal communication, 3/10/2008]. This concept of immediate response raises the question of how geopotential height index values can be incorporated into long lead-time forecasts.

The results of this study as well as those of Grantz et al. [2005] imply that an improved skill of streamflow forecasting is achieved at shorter lead-times. Since precipitation is an immediate response to geopotential heights it seems logical to conclude that there is no lag time between precipitation and the geopotential height index. Rather the geopotential heights are responsible for wintertime precipitation (falling as snow in the NPRB) when it is actually occurring (ONDJFM) and the three month lead-time is actually the typical time between when the snowfalls and the snow melts. We see a strong skill associated with the forecast utilizing OND(-1) geopotential heights because during those months the 500 mbar geopotential height index values are immediately driving the snowfall which settles, compacts and then begins melting several months later and is the prominent source of streamflow volume. Similar logic can be applied to the JAS(-1) time period. In mountainous regions, some precipitation may fall as snowfall but a substantial portion may still be falling in the form of rain due to the warmer temperatures of July, August and September. Due to the precipitation falling as rain and not snow, it is not accumulating as snowpack (which melts several months later and contributes to AMJJ streamflow) and therefore is not recognized as a skillful predictor in the model. Another question might be raised as to why not just use the actual snowpack amounts as measured at snow telemetry sites as opposed to incorporating Z_{500}.

The Natural Resource Conservation Service (NRCS) currently operates SNOTEL (snow water equivalent telemetry sites) throughout the west. However, January 1st data is only available back into the mid 1980's when most sites transferred from snowcourse sites to automated telemetry sites. Prior to the mid 1980's actual snowpack depth was only available for the months of March, April and May. The work of Moser et al. [2008] concludes a strong correlation between streamflow and snow water equivalent recorded by SNOTEL sites in the NPRB mountainous headwater regions. The results of this study suggest that Z_{500} index values can be a skillful predictor of winter precipitation and thus spring streamflow, especially in mountainous NBRB regions where the precipitation falls as snow. Therefore, if the 500 mbar geopotential height index values can be used as predictors of snowfall it can be concluded that for the NPRB this snowfall would result in AMJJ streamflow volumes.

CONCLUSION

A method for developing spatial-temporal relationships between large scale oceanic-atmospheric influences and incorporating those relationships into the development of exceedance probability forecasts for the North Platte River was performed. The North Platte River Basin is in a challenging location in terms of predefined climate index signals. The correlation between North Platte River streamflow volumes and the predefined Niño 3.4, PDO and AMO climate indices were found, in general, to be insignificant, thus creating the need to locate significant regions of oceanic-atmospheric variability. SVD was used to identify significant (>90%) spatial-temporal regions of SST and Z_{500} such that temporal expansion series (1^{st} mode) found could be used to generate exceedance probability forecasts. Due to the continuous nature of the exceedance probability forecast, it is especially useful because it allows the forecast user to assess the forecasted amount of streamflow at different levels of risk. The forecast model was applied at two lead-times, three month—OND(-1) and six month—JAS(-1). The results of the modeling process reveal that SSTs are a skillful six month lead-time predictor whereas Z_{500} produce more skillful three month lead-time forecasts. Various years were selected to provide examples of good (high cross validated LEPS skill score) and poor forecasts. Over the 57 years used in this analysis, more good forecasts were developed versus poor forecasts, thus indicating that large scale oceanic-atmospheric climate variability is applicable to generating skillful long lead-time forecasts. The significant contribution of this work was the application of singular value decomposition techniques to identify predictors to be utilized in long lead-time streamflow forecasting models.

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TABLE AND FIGURE CAPTIONS

Table 2.1: Correlation table of current seasonal (spring-summer, AMJJ) streamflow (Q) and previous [JAS (-1) and OND(-1)] seasonal climate indices (Nino 3.4, PDO, AMO) and Temporal Expansion Series (1^{st}, 2^{nd} and 3^{rd} modes) for SSTs[1,2,3] and Z500[1,2,3].

Table 2.2: Weighting and LEPS [Calibration (Cal) and Cross Validation (CV)] score skill table of current seasonal (spring-summer, AMJJ) streamflow (Q) and previous [JAS (-1) and OND(-1)] seasonal climate indices (Nino 3.4, PDO, AMO) and Temporal Expansion Series (1^{st}, 2^{nd} and 3^{rd} modes) for SSTs[1,2,3] and Z500[1,2,3].

Figure 2.1: North Platte River Basin and USGS Streamflow Stations Location Map.

Figure 2.2: Heterogeneous correlation map showing significant [$|r| > 0.21$ for 90% ($p < 0.1$) significance threshold] SST regions as related to NPRB streamflow stations for JAS(-1) six month lead-time.

Figure 2.3: Examples of poor and good forecasts for JAS(-1) SSTs and individual streamflow stations.

Figure 2.4: Heterogeneous correlation map showing significant [$|r| > 0.21$ for 90% ($p < 0.1$) significance threshold] Z_{500} regions as related to NPRB streamflow stations for OND(-1) three month lead-time.

Figure 2.5: Examples of poor and good forecasts for OND Z_{500} index values and individual streamflow stations.

Table 2.1

JAS(-1)	Q1 (AMJJ)	Q2 (AMJJ)	Q3 (AMJJ)	Q4 (AMJJ)	OND(-1)	Q1 (AMJJ)	Q2 (AMJJ)	Q3 (AMJJ)	Q4 (AMJJ)
Nino 3.4	-0.03	-0.07	0.02	0.17	Nino 3.4	-0.04	-0.09	0	0.19
PDO	0.02	-0.03	-0.04	0.04	PDO	-0.12	-0.15	-0.15	-0.01
AMO	-0.24	-0.25	-0.27	-0.37	AMO	-0.17	-0.15	-0.16	-0.34
SST1	0.43	0.41	0.49	0.54	SST1	0.52	0.49	0.53	0.58
SST2	-0.09	-0.16	-0.06	0.25	SST2	-0.09	-0.16	-0.04	0.25
SST3	0.09	0.07	-0.17	0.03	SST3	0.17	-.06	-0.11	-0.00
500mb1	0.38	0.42	0.43	0.38	500mb1	0.52	0.53	0.56	0.45
500mb2	-0.05	-0.04	-0.06	0.16	500mb2	-0.02	-0.05	-0.06	0.16
500mb3	0.03	-0.10	0.06	0.00	500mb3	0.15	-0.11	-0.02	-0.02

Table 2.2

JAS(-1)	Q1 (AMJJ)	Q2 (AMJJ)	Q3 (AMJJ)	Q4 (AMJJ)	OND(-1)	Q1 (AMJJ)	Q2 (AMJJ)	Q3 (AMJJ)	Q4 (AMJJ)
Nino 3.4	0%	0%	0%	0%	Nino 3.4	33%	95%	77%	0%
PDO	0%	0%	0%	0%	PDO	0%	0%	3%	2%
AMO	100%	100%	100%	100%	AMO	67%	5%	20%	98%
Cal Skill	9.2%	11.6%	8.9%	13.8%	Cal Skill	5.0%	6.1%	5.2%	8.8%
CV Skill	***1.0%***	***0.7%***	***-1.4%***	***1.4%***	***CV Skill***	***-8.6%***	***-4.5%***	***-9.6%***	***-0.7%***
SST1	100%	100%	100%	100%	SST1	100%	100%	100%	100%
SST2	0%	0%	0%	0%	SST2	0%	0%	0%	0%
SST3	0%	0%	0%	0%	SST3	0%	0%	0%	0%
Cal Skill	16.4%	21.4%	18.2%	20.6%	Cal Skill	16.5%	21.4%	18.1%	16.6%
CV Skill	***7.3%***	***8.5%***	***8.1%***	***10.2%***	***CV Skill***	***2.9%***	***6.2%***	***5.7%***	***4.7%***
500mb1	100%	100%	100%	100%	500mb1	100%	100%	100%	100%
500mb2	0%	0%	0%	0%	500mb2	0%	0%	0%	0%
500mb3	0%	0%	0%	0%	500mb3	0%	0%	0%	0%
Cal Skill	16.7%	15.4%	15.3%	14.3%	Cal Skill	23.9%	25.1%	25.0%	20.3%
CV Skill	***3.6%***	***3.3%***	***5.7%***	***4.5%***	***CV Skill***	***12.8%***	***14.6%***	***13.7%***	***10.4%***

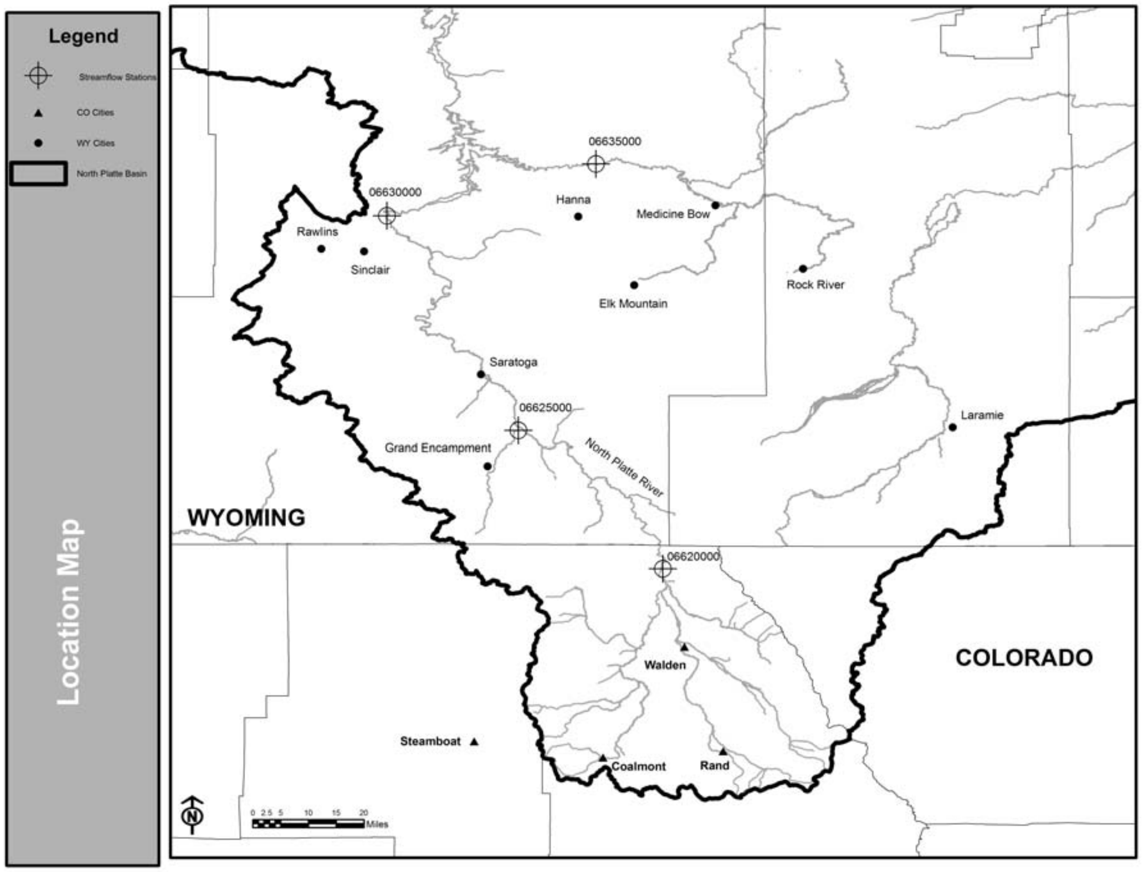

Legend
Streamflow Stations
CO Cities
WY Cities
North Platte Basin
Location Map
06635000
06630000
Hanna
Medicine Bow
Rawlins
Sinclair
Rock River
Elk Mountain
Saratoga
06625000
Laramie
Grand Encampment
North Platte River
WYOMING
06620000
COLORADO
Walden
Steamboat
Coalmont
Rand
0 2.5 5 10 15 20
Miles

Figure 2.1

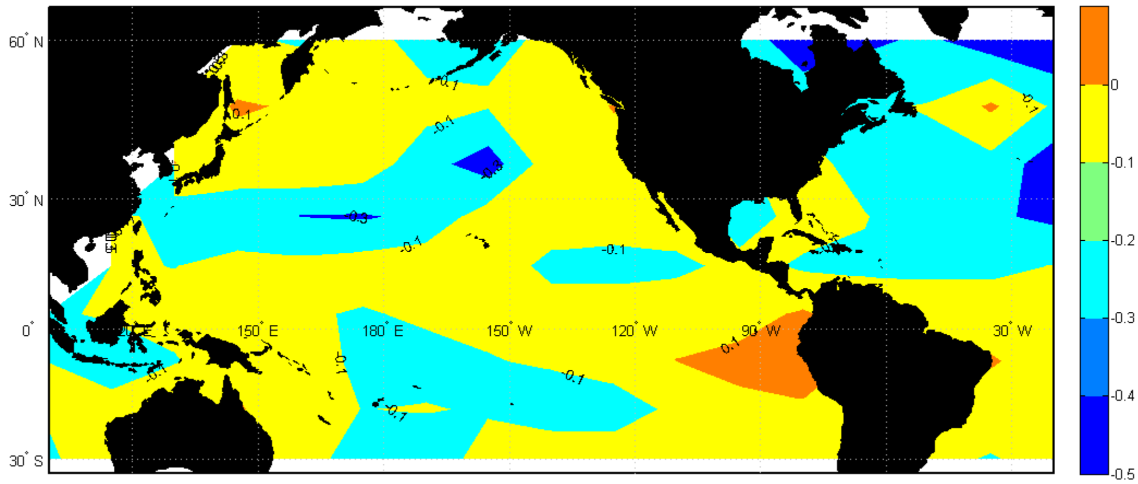


Figure 2.2

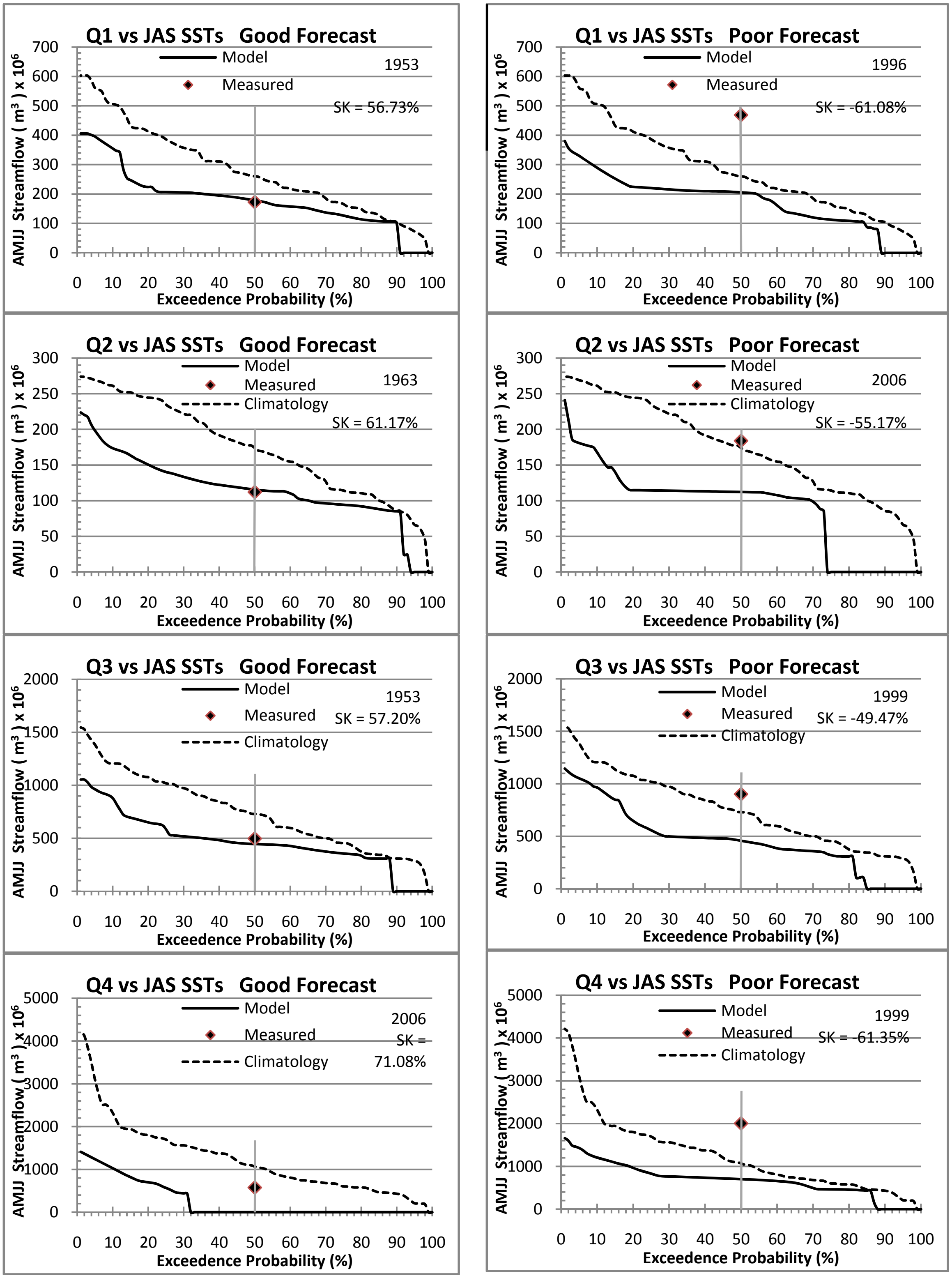
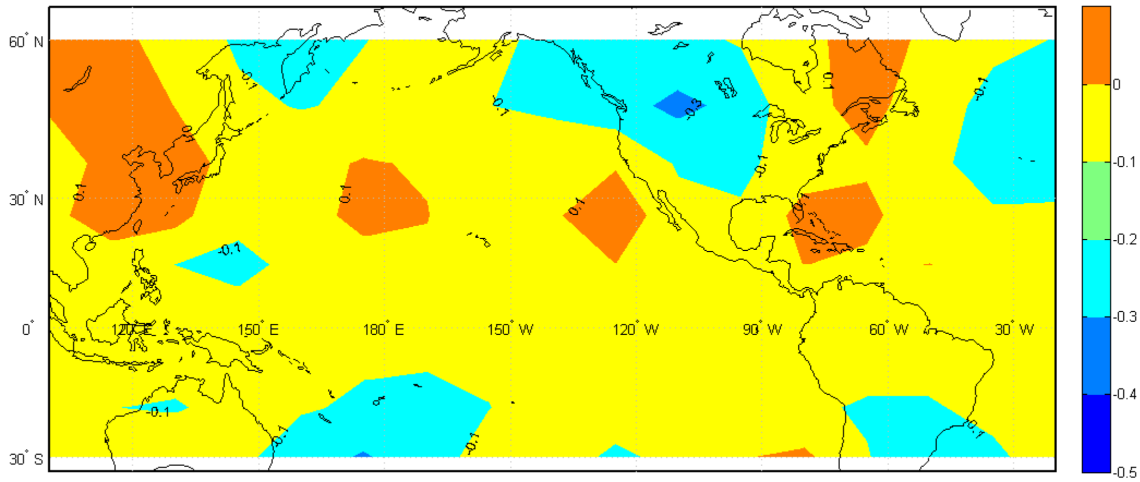
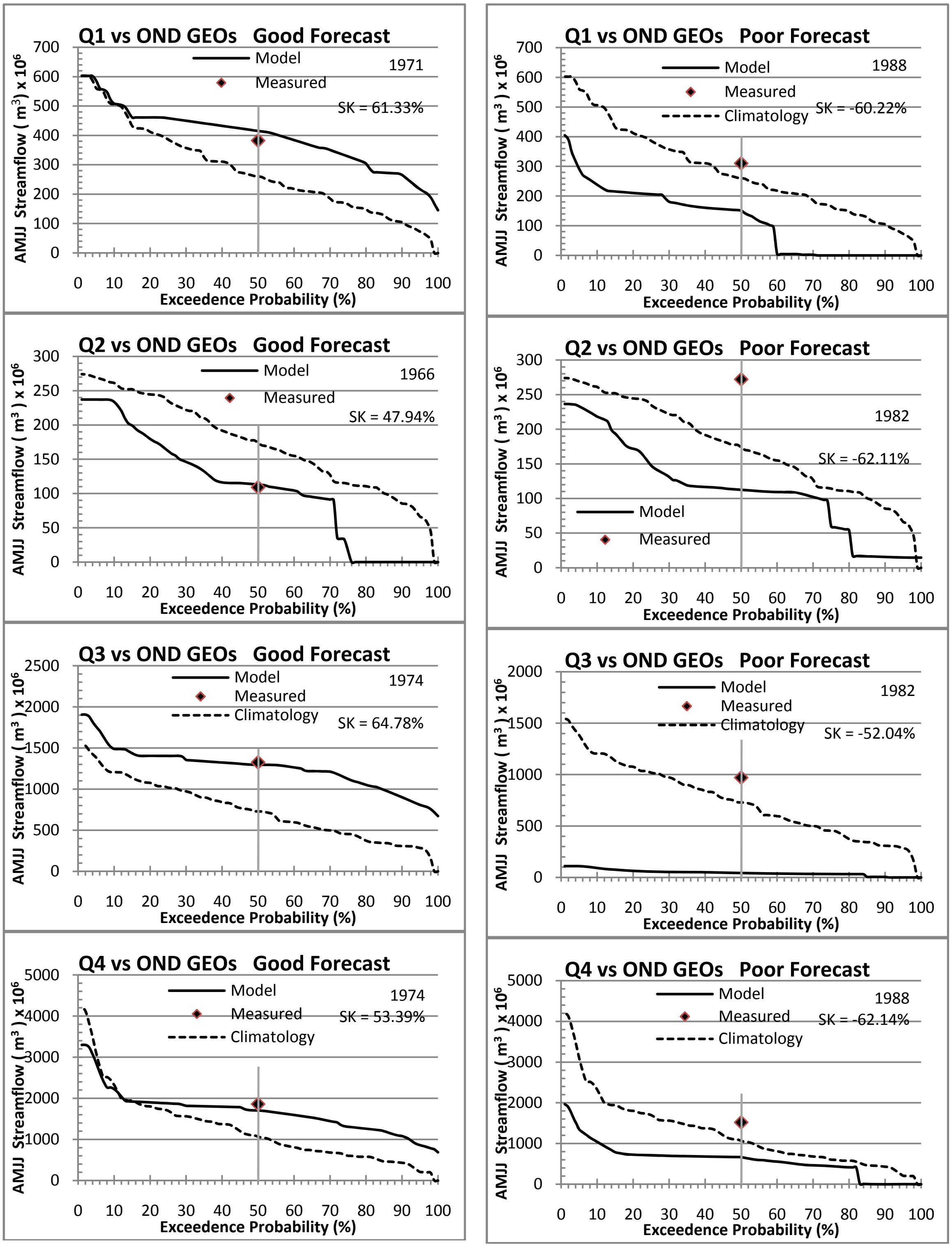

Q1 vs JAS SSTs Good Forecast
Model
Measured
1953
SK = 56.73%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q1 vs JAS SSTs Poor Forecast
Model
Measured
1996
SK = -61.08%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q2 vs JAS SSTs Good Forecast
Model
Measured
Climatology
1963
SK = 61.17%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q2 vs JAS SSTs Poor Forecast
Model
Measured
Climatology
2006
SK = -55.17%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q3 vs JAS SSTs Good Forecast
Model
Measured
Climatology
1953
SK = 57.20%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q3 vs JAS SSTs Poor Forecast
Model
Measured
Climatology
1999
SK = -49.47%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q4 vs JAS SSTs Good Forecast
Model
Measured
Climatology
2006
SK =
71.08%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q4 vs JAS SSTs Poor Forecast
Model
Measured
Climatology
1999
SK = -61.35%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)

Figure 2.3



60° N
30° N
0°
30° S
120° E
150° E
180° E
150° W
120° W
90° W
60° W
30° W
0
-0.1
-0.2
-0.3
-0.4
-0.5

Figure 2.4



Q1 vs OND GEOs Good Forecast
Model
Measured
1971
SK = 61.33%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q1 vs OND GEOs Poor Forecast
Model
Measured
Climatology
1988
SK = -60.22%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q2 vs OND GEOs Good Forecast
Model
Measured
1966
SK = 47.94%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q2 vs OND GEOs Poor Forecast
1982
SK = -62.11%
Model
Measured
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q3 vs OND GEOs Good Forecast
Model
Measured
Climatology
1974
SK = 64.78%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q3 vs OND GEOs Poor Forecast
Model
Measured
Climatology
1982
SK = -52.04%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q4 vs OND GEOs Good Forecast
Model
Measured
Climatology
1974
SK = 53.39%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)
Q4 vs OND GEOs Poor Forecast
Model
Measured
Climatology
1988
SK = -62.14%
AMJJ Streamflow (m³) x 10⁶
Exceedence Probability (%)

Figure 2.5

A New Method for Tracing Seepage from CBNG Water Holding Ponds in the Powder River Basin, Wyoming

Basic Information

Title:	A New Method for Tracing Seepage from CBNG Water Holding Ponds in the Powder River Basin, Wyoming
Project Number:	2008WY43B
Start Date:	3/1/2008
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	1
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Surface Water, Water Quality
Descriptors:	None
Principal Investigators:	Shikha Sharma, Carol Frost, Katta J Reddy

Publications

There are no publications.

A New Method for Tracing Seepage from CBNG Water Holding Ponds in the Powder River Basin, Wyoming

Final Report for a 2-year project (March 2008 – February 2010)

PIs: Shikha Sharma, K.J. Reddy, and Carol Frost

Abstract:

The proposed work will establish and verify the utility of a low-cost and innovative approach for understanding *"Groundwater contamination caused by seepage out of CBM water holding ponds,"* which has been identified as one of the critical areas of research under the CBNG Related Issues category in the Wyoming Water Research Program Request for Proposals (WRP RFP, 2008). Groundwater degradation caused by infiltration from CBNG water retention ponds is an issue of immense importance because groundwater is a major source for stock water, irrigation and drinking water for many small communities and ranchers in the Powder River Basin, Wyoming. It is necessary to develop a tracer that can fingerprint this water in order to trace seepage of water from these ponds into shallow aquifers. Strontium isotopes and other geochemical tracers have limited application in some instances because of significant contributions of these elements from local lithologies and high analysis costs. This study evaluates a low cost tracer that is less readily overwhelmed by near-surface sources.

Based upon preliminary analyses of CBNG co-produced water from the Powder River Basin, Wyoming, we suggest that the carbon concentrations and isotopic composition of Dissolved Inorganic Carbon ($\delta^{13}C_{DIC}$) can be used as a natural tracer for fingerprinting CBNG co-produced water. Our results show that CBNG co-produced water has strongly positive $\delta^{13}C_{DIC}$ (+12 to +22‰) that is readily distinguished from the negative $\delta^{13}C$ of most surface and groundwaters (-10 to -15‰). Furthermore, the DIC concentrations in co-produced water samples are also high (>100 mg C/l) compared to the 20-50 mg C/l in ambient surface and groundwaters of the region. The distinctively high $\delta^{13}C$ and DIC concentrations allow us to identify surface and groundwaters that have incorporated CBNG co-produced water and can also be used to track the CBNG produced water infiltrating from the ponds. Accordingly, we suggest that the $\delta^{13}C_{DIC}$ and DIC concentrations of water can be used for long term monitoring of infiltration of CBNG co-produced water from the CBNG water holding ponds (Sharma and Frost, 2008).

Samples will be collected from the CBNG discharge wells, water holding ponds and monitoring wells in the Powder River Basin and analyzed for $\delta^{13}C_{DIC}$ and DIC concentrations, pH, dissolved oxygen (DO), electrical conductivity (EC), major cations (e.g., Ca, Mg, Na, and K), and major anions (e.g., alkalinity, sulfate, chloride, fluoride, nitrate, and phosphate) to assess changes in water quality as the CBNG water migrates along the recharge flow path.

The results from this study will demonstrate how we can trace the seepage out of CBNG water holding ponds using a **low cost stable isotope approach**. A graduate student will be an integral part of this project. The project results will be presented at state, regional, and national meetings and published in appropriate peer-reviewed journals.

Objectives

Potential groundwater degradation caused by infiltration from CBNG water holding ponds is an issue of immense importance in the state of Wyoming where infiltration ponds are a common method for disposal of CBNG co-produced water. The objective of this study is to establish the utility of a new method for tracing infiltration of CBNG water from these ponds to near surface aquifers and shallow groundwaters. The method involves using stable isotope of carbon in dissolved inorganic carbon ($\delta^{13}C_{DIC}$) and DIC concentrations for fingerprinting CBNG co-produced water. The specific tasks which will be undertaken to attain this broad objective include:

1) The CBNG co-produced water samples will be collected from discharge points, corresponding retention ponds and a series of monitoring groundwater wells at selected sites in Powder River Basin for a period of 2 years.
2) Samples will be analyzed for $\delta^{13}C$ of DIC and DIC concentrations in water at the University of Wyoming Stable Isotope Facility.
3) Isotope mixing models will be used to calculate the fraction of CBNG co-produced water incorporated into the shallow groundwaters.
4) The geochemical parameters (pH, EC, major cations, major anions) will be used to assess the impact of infiltration of CBNG co-produced water on the ground water quality.
5) Convey research results to WY-DEQ, water users, landowners, and CBNG operators through project demonstrations, workshops, and local meetings.

Methods

Study sites have been chosen in Sheridan, Campbell and Johnson Counties (see Figure1). The sites were selected based on following criteria:

- All impoundment sites had upstream and downstream monitoring wells installed at similar depths (~40-140 feet) and in similar lithological horizons.
- All impoundments had received CBNG water for at least 1-2 years and had similar water holding capacity.
- Lithological logs were available for all monitoring wells.

The water sampling is done in accordance with the SAP (Sample Analysis Procedures) protocols of Wyoming DEQ-Water Quality Division. The monitoring wells are purged at rate of less than 1L /min with a submerged bladder pump until 3 casing volumes of water was removed. Water samples are collected when all field parameters (pH, EC, and Temperature) stabilized to within 10% for 3 consecutive readings. Three set of samples are collected at each sampling site 1) one sample for $\delta^{13}C_{DIC}$ and DIC concentration measurement 2) Duplicate samples for $\delta^{18}O$ and δD measurement and 3) Duplicate samples for alkalinity, major anions (phosphate, nitrate, fluoride, chloride, sulfate), and major cations (aluminum, boron, barium, cadmium, chromium, copper, iron, manganese molybdenum, lead, zinc, sodium, magnesium).

The samples for dissolved inorganic carbon are taken into a 60mm syringe and passed through a 0.45 µm Whatman filter attached to the end of the syringe and filled into a 30mL Wheaton glass serum vial. Two drops of benzalkonium chloride are added to halt biologic activity. The vials are topped with a Teflon seal and capped with an aluminum top. The aluminum tops are crimped to close the vials. The $\delta^{13}C_{DIC}$ is measured on a Gas Bench-II device coupled to a Finnigan DELTA plus mass spectrometer in the central Stable Isotope Facility at the University of Wyoming. The reproducibility and accuracy was monitored by replicate analysis of internal lab standards and was better than ± 0.1 ‰. The $\delta^{13}C_{DIC}$ values are reported in per mil relative to V-PDB. The DIC concentrations in samples were also quantified from the mass spectrometry data. Three $NaHCO_3$ stock solutions of different DIC concentrations were prepared for this purpose. DIC concentrations were then quantified based on the peak areas of the mass 44-ion trace of these standards. Plotting peak area of CO_2 vs. concentration of DIC in these standards gives an excellent correlation (r^2=0.995), indicating that DIC concentrations of the samples could be quantified using this method. The relative standard uncertainty of the DIC concentration measurement in this study was ± 3%. The samples for $\delta^{18}O$ and δD are taken in 10 mL glass vials. The sample is filled up to the brim avoiding any headspace and then capped and sealed with layer of parafilm. The $\delta^{18}O$ and δD measurement is done using the Los Gatos Liquid-water Isotope Analyzer housed in University of Wyoming Stable isotope Facility. Samples for alkalinity, major anions and major cations are taken in Fisher 1L plastic bottles which had been previously acid washed for three hours in a nitric acid bath at a pH below 2. Upon return to Laramie, these samples are filtered with 0.45 µm filters before testing for alkalinity, anions (aluminum, boron, barium, cadmium, chromium, copper, iron, manganese, molybdenum, lead, zinc, calcium, potassium, and arsenic), and cations (fluoride, chloride, nitrate, phosphate, and sulfate). Alkalinity is tested in the University of Wyoming Water Quality Lab using the 702 SM Titrino automatic titrator manufactured by Brinkmann. Anions and cations are measured using the ICP-MS and IC housed in UW Soil Testing Laboratory and Geochemistry Analytical Laboratory respectively.

Principal Findings

Samples were collected from seven sites located in the Tongue and Powder River watersheds of the Powder River Basin (**Fig. 1**). At each sampling location, we collected water from the outfall, impoundments into which this water is discharged, and samples from monitoring wells installed upstream and downstream of the impoundment. These study sites were chosen because they were instrumented with monitoring wells both upstream and downstream from the impoundment, had received CBNG water for at least 2 years, and had a water holding capacity of at least 10 acre feet. In order to study the effects of seasonal changes, each location was sampled during the low flow season of September 2008 and again during the snowmelt season of May 2009.

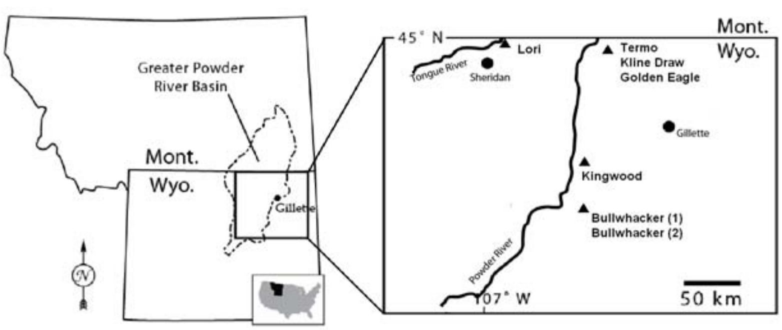


Figure 1: Map showing location of sampling sites in Powder River Basin

Sampling trips were taken in August, September, and November of 2008, and May of 2009. The scientists from Wyoming Department of Environmental Quality office in Sheridan helped us sample four study sites namely Termo, Gloden Eagle, Kline Draw located in northwest corner of Campbell county and Lori located in the north-central Sheridan county of Powder river basin (**Figure 1**). Sampling trips were taken to sample three sites, Kingwood, Bullwhacker (1) (P23-32-4376), and Bullwhacker (2) (P23-30-4376) in Johnson County with the assistance of WWC Engineering, an environmental consulting firm based in Sheridan. All the samples have been analyzed for $\delta^{13}C_{DIC}$ and, as hypothesized, all water samples collected from the outfalls and ponds have high $\delta^{13}C_{DIC}$ values in range of +12 to +20‰ during the fall and from to +1‰ to +18‰ durig the spring (**Figure 2**). The ponds and outfalls at all the sites had very similar $\delta^{13}C_{DIC}$ signatures during the fall, indicating that the pond water has not undergone any significant change in carbonate chemistry due to dissolution effects or due to CO_2 exchange with atmosphere. The monitoring wells had lower $\delta^{13}C_{DIC}$ values ranging from -13‰ (interpreted as not affected by seepage from ponds) to -6‰ (interpreted as effected by seepage). During the spring, some of the ponds show lower $\delta^{13}C_{DIC}$ signatures compared to the corresponding outfall. We hypothesize that during spring these impoundments may have been diluted by snowmelt water which has lower $\delta^{13}C_{DIC}$ signatures.

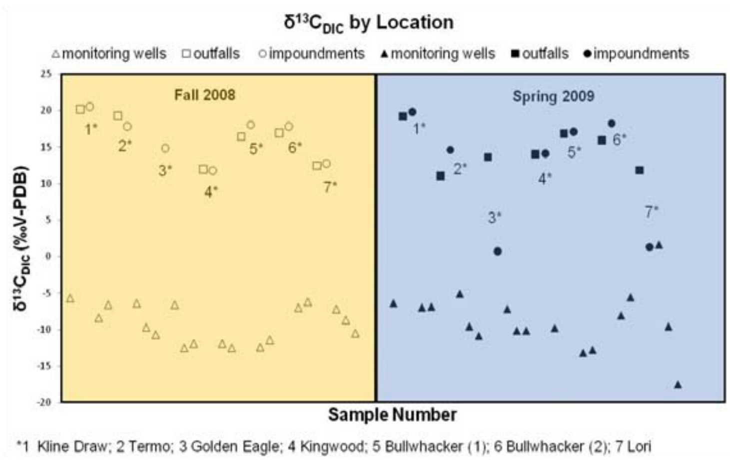


Figure 2: Samples collected from ponds and outfalls have higher $\delta^{13}C_{DIC}$ values than water samples from all monitoring wells. During Spring, 2009, samples from Golden Eagle and Lori impoundments show much lower $\delta^{13}C_{DIC}$ values.

The carbon isotopic distinction between the two bodies of water (methanogenic impoundment water and non-methanogenic ambient water in monitoring well) is the basis for the use of $\delta^{13}C_{DIC}$ as a tracer. It can be expected that if methanogenic water from CBNG impoundments with high $\delta^{13}C_{DIC}$ values is infiltrating to the subsurface, it will elevate the $\delta^{13}C_{DIC}$ values of ambient groundwater. However, it is difficult to estimate the exact contribution of CBNG co-produced water using this approach mainly because there are several other contributors to the total DIC of sample like carbon from carbonate dissolution, snowmelt, infiltrating surface waters etc. We used a Keeling plot approach to determine the major source of DIC. Using this approach the $\delta^{13}C_{DIC}$ values of samples are plotted against 1/DIC concentration and the regression of the data yields a y-intercept value, representing $\delta^{13}C_{DIC}$ of added DIC (**Figure 3**).

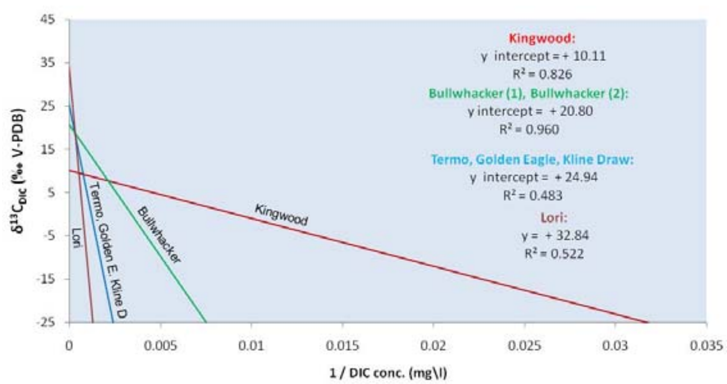


Figure 3: Plot of $\delta^{13}C_{DIC}$ against 1/DIC concentrations where the Y intercept represents the $\delta^{13}C$ signature of added DIC

$$\delta^{13}C_{sample}\,(DIC)_{sample} = \delta^{13}C_{ambient}\,(DIC)_{ambient} + \delta^{13}C_{added}\,(DIC)_{added}$$

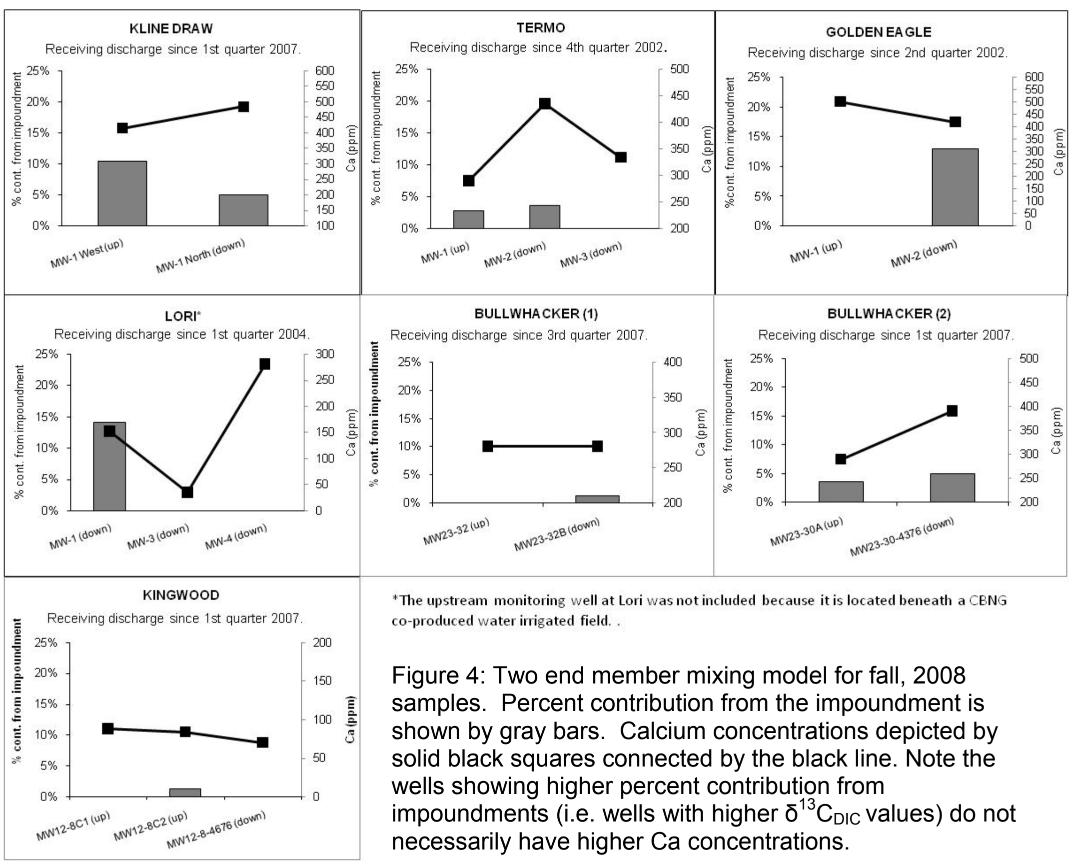
$$\delta^{13}C_{sample} = \delta^{13}C_{ambient}\ (\delta^{13}C_{ambient} - \delta^{13}C_{added})\ *1/(DIC)_{sample}\ + \delta^{13}C_{added}$$

Addition of DIC with $\delta^{13}C$ values >10 ‰ is strong evidence that bicarbonate originating from biogenic methanogenic processes is the major source of DIC at these sites rather than carbonate rock dissolution which contributes DIC with $\delta^{13}C$ values of ~1-2 ‰. Another line of evidence supporting that carbonate dissolution is not a major source of DIC to the waters in monitoring wells is that samples from monitoring wells showing higher $\delta^{13}C_{DIC}$ values (indicated by higher % contribution from methanogenic waters using our $\delta^{13}C$ mixing model) do not necessarily show higher Ca concentrations (Figure 4). Therefore, we can presume that the higher $\delta^{13}C_{DIC}$ values in these monitoring well samples are due to contribution from methanogenic water with higher $\delta^{13}C$ signatures.

Assuming that the co-produced water infiltrating from the impoundment and the ambient water in the sampled aquifer at the monitoring well site are the only two sources contributing to the total DIC, a simple two end member isotope mixing model can be used to estimate the fraction of CBNG co-produced water incorporated into the groundwaters at the monitoring well sites:

$$\delta^{13}C_{mw}\ (DIC)_{mw} = \delta^{13}C_{iw}\ f_{iw}\,(DIC)_{iw} + \delta^{13}C_{amb}\ (1- f_{iw})\ (DIC)_{amb}$$

Where the subscripts “mw”, “iw”, and “amb” indicate the carbon isotope ratio ($\delta^{13}C$), fractional contribution (f), or DIC concentration (DIC) of monitoring wells, impoundment and ambient water samples, respectively.



*The upstream monitoring well at Lori was not included because it is located beneath a CBNG co-produced water irrigated field. .

Figure 4: Two end member mixing model for fall, 2008 samples. Percent contribution from the impoundment is shown by gray bars. Calcium concentrations depicted by solid black squares connected by the black line. Note the wells showing higher percent contribution from impoundments (i.e. wells with higher $\delta^{13}C_{DIC}$ values) do not necessarily have higher Ca concentrations.

Ambient $\delta^{13}C_{DIC}$ values were considered to be the lowest $\delta^{13}C_{DIC}$ value obtained from the monitoring wells in each study area. During fall 2008, ambient water $\delta^{13}C_{DIC}$ values were -10.7‰ at Kline Draw, Termo, and Golden Eagle; -12.5‰ at Bullwhacker (1), and Bullwhacker (2); -12.5‰ at Kingwood; and -10.5‰ at Lori. All of these samples have $\delta^{13}C_{DIC}$ values within the expected isotopic range of ambient groundwaters (Mook and Tan, 1991; Sharma and Frost, 2008). The total concentration of DIC for each sample was calculated from the addition of the concentrations of carbonate, bicarbonate, and carbonic acid species.

Results from the isotope mixing model from fall 2008 data suggest that both the upstream and downstream monitoring wells can be influenced from infiltration of CBNG co-produced water from the impoundments. The fraction of contribution from CBNG impoundments ranges from 0-10.4% in upstream wells to 0-14.1% in downstream wells **(Figure 4)**. We did not use this model for samples collected in spring 2009 because there was excessive dilution of impoundment water with isotopically light snowmelt water significantly lowering the $\delta^{13}C_{DIC}$ values of the CBNG water in the impoundments at the Golden Eagle and Lori sites. This dilution reduced the isotopic range between the two end-members of the mixing model, the impoundment water (iw) and water in the monitoring well (mw), resulting in an exaggeration of calculated fractional contribution of impoundment water. We would like to point out that this simple two member mixing model approach has several limitations: 1) it does not account for other potential sources of DIC to the water in the monitoring well, e.g. dissolution of carbonates as water percolates through the different lithological horizons, 2) it does not account for any other source of water to the monitoring well, such as snow melt recharge or water seeping in from overlying or underlying aquifers, and 3) it does not account for uncertainty in the estimated proportions due to changing isotopic composition of the two end-members during different seasons, years, etc.

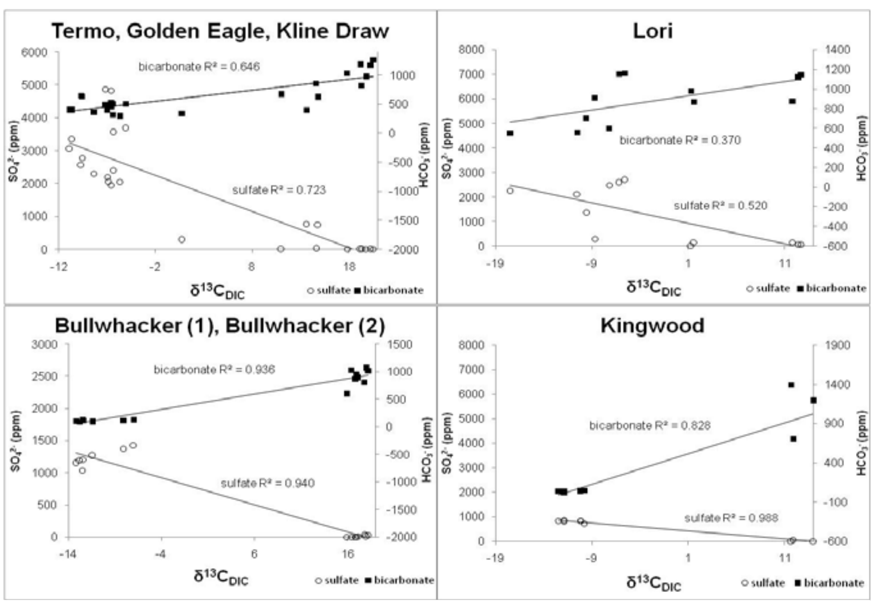
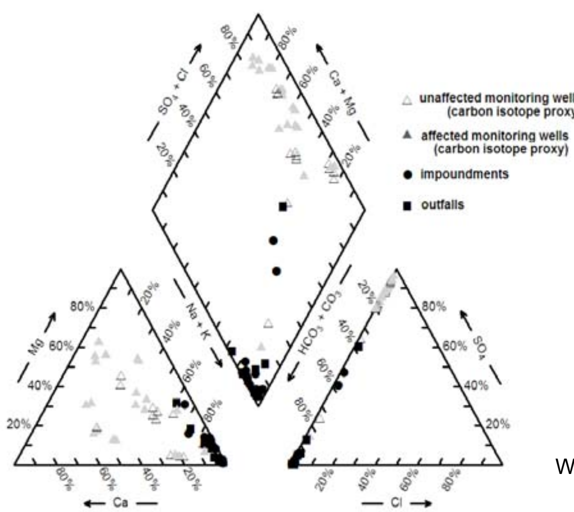


Figure 5: Graph showing positive correlation of $\delta^{13}C_{DIC}$ with HCO_3 concentration (;) and negative correlation with SO_4 (#) concentrations

The major anion chemistry of the water samples indicates that the methanogenic waters with high $\delta^{13}C_{DIC}$ values have low concentrations of sulfate and high concentrations of bicarbonate (**Figure 5**). The low SO_4^{2-} and high HCO_3^- concentrations in CBNG co-produced waters are probably the result of bacterially-mediated oxidation–reduction reactions in the coal zones (Van Voast 2003; Rice et al., 2008; Brinck et al., 2008). To compare major ion content of co-produced water from outfall and impoundments to monitoring wells geochemical variation piper diagrams were made with AqQaChem water analysis spreadsheet software from RockWare. Outfall and impoundment water samples are predominantly of the Na-HCO_3- type as has been documented by previous studies (Van Voast, 2003; Patz et al., 2004; Brinck and Frost, 2007; Jackson and Reddy, 2007; Brinck et al., 2008; Healy et al., 2008; Rice et al, 2008). The samples from monitoring wells are highly variable probably due to site to site variation in local lithologies. However, most of these samples are SO_4^{2-} dominant. There is no clear geochemical difference between wells that have received some contribution of methanogenic water based on the carbon isotope proxy model, and those that have not. The TDS (Total Dissolved Solids) values in the waters of the monitoring wells is generally higher than methanogenic waters from outfalls and impoundments and could be the result of series of dissolution reactions which take place as the water recharging these deep aquifers infiltrates through the various lithologies (Wheaton and Brown, 2005; Frost and Brinck, 2005; Brinck and Frost 2007). The average TDS values of samples collected from both seasons from wells that have received some CBNG discharge are very similar to wells that show no indication of infiltration based on out carbon isotope model. This suggests that geochemical processes that occur during infiltration are the most important contributor to shallow groundwater TDS (Brinck and Frost, 2007) or that co-produced water influence in affected monitoring wells is not significant enough to alter the TDS. The SAR (Sodium Absorption Ratio) is higher in methanogenic waters due to higher Na concentrations mainly because the high HCO_3 concentration causes all the Ca and Mg to precipitate as carbonate.



	TDS mg/L	SAR	SO_4 mg/L	HCO_3 mg/L	Mg mg/L	Ca mg/L	Na mg/L
Termo, Golden Eagle, Kline Draw							
Outfalls and Impoundments	1970	25.2	167	1272	28	16	475
Affected Monitoring Wells (5.0%)*	5335	4.7	2993	652	492	411	580
Unaffected Monitoring Wells	5326	6.9	2950	783	351	417	744
Kingwood							
Outfalls and Impoundments	2055	18.9	27	1472	24	10	480
Affected Monitoring Wells (0.4%)*	1378	9.5	854	49	11	92	360
Unaffected Monitoring Wells	1303	9.3	798	67	9	83	335
Bullwhacker (1), Bullwhacker (2)							
Outfalls and Impoundments	1908	13.4	11	1352	34	16	413
Affected Monitoring Wells (2.4%)*	2095	2.9	1270	163	84	333	223
Unaffected Monitoring Wells	2285	2.5	1039	195	60	280	180
Lori**							
Outfalls and Impoundments	2235	42.2	72	1536	5	9	578
Affected Monitoring Wells (4.7%)*	3514	14.7	1320	1091	142	93	812
Unaffected Monitoring Wells	3627	11.1	1510	1012	147	177	735

*The average percent contribution of impoundment water to monitoring wells, based on the carbon isotope two end-member mixing model.
**The upstream monitoring well, Lori PD-1, was not included because it was drilled into methanogenic coal.

Where: SAR = (Na^{2+} meq/L) / √ [(Ca^{2+} meq/L) + (Mg^{2+} meq/L) / 2]

Figure 6 Piper diagram comparing impoundment, outfall, and monitoring well water samples from fall 2008 and spring 2009. Monitoring wells are indicated as being affected or unaffected by CBNG co-produced water based on the carbon isotope/dissolved inorganic proxy. The table shows average TDS, SAR , SO_4^{2-} , HCO_3^-, Ca, Mg and Na values of samples collected from both seasons (spring 2008 and fall 2009) for each study site.

We hypothesize the as CBNG co-produced water infiltrates through the different lithologies concentrations of Ca and Mg increase due to dissolution resulting in the decrease of SAR values. This is likely because calcite, dolomite and gypsum are the common minerals in shallow soil and bedrock profile of the Powder River Basin and their dissolution increases the Ca, Mg and SO4 ion concentrations in infiltrating waters decreasing the SAR (Wheaton and Brown, 2005). However no difference is seen in wells affected and not affected by impoundment seepage.

However, in this study the highest impacted monitoring well shows only 14% contribution from CBNG co-produced water. Continued monitoring is required to understand how the geochemical parameters of these well waters change as the fractional contribution from CBNG co-produced water increases over time.

This project also partially supported another study entitled *"Stable Isotope and Geochemical Analyses of Wyoming Coalbed Aquifers: A new tool to minimize water production and maximize gas production in a coalbed natural gas play"*. This is a MS thesis project of Scott Quillinan graduate student in department of Geology and Geophysics, co-advised by Drs. Frost and Sharma. The primary funding sources of this project are Anadarko Petroleum and Wyoming Geological Survey. However, partial financial support in terms of stable isotope sample analysis and sampling supplies was provided by this WWDC-USGS funded project. In this study we are investigating isotopic and water chemistry over a wide variety of attributes in the Atlantic Rim and Powder River Basin CBNG plays. Preliminary samples have been collected and geospatial modeling of the data collected so far indicates that the $\delta^{13}C_{DIC}$ signatures used in conjunction with geochemical data and geological information can be effectively used for 1) CBM reservoir characterization 2) coal zone distinction and 3) test for hydraulic isolation and well completion efficiency. In Atlantic Rim area the carbon isotope signatures of CBNG co-produced waters shows a good correlation with water/gas ratios i.e. higher $\delta^{13}C_{DIC}$ signatures are correlated with low water/gas ratios. A set of sample samples collected from well-heads located in same coal zone (name not disclosed due to proprietary issues) and located in close proximity showed highly variable $\delta^{13}C_{DIC}$ values **(Figure 7)**. We found that well-head water samples (collected from same age wells) having a very low $\delta^{13}C_{DIC}$ value had very high water to gas ratios indicating that during the process of de-watering significant amount of water was being withdrawn from overlying and/or underlying aquifers at these sites. The initial results indicate that the $\delta^{13}C_{DIC}$ signatures of co-produced waters could potentially be used as an exploratory tool for planning locations of future expansion of CBNG development in areas where gas production can be maximized with minimum water production. Another set of preliminary samples were collected from CBNG wells completed in Big George Coal in Powder River basin and they show some very interesting trends. The high $\delta^{13}C_{DIC}$ values correlate with low water/gas ratios in the south-eastern part of the study area. However, in the central and some portions of the northwestern corner of the study area low $\delta^{13}C_{DIC}$ values correlate with low water to gas ratios. In the central part of the basin some of this anomaly overlaps with the enormously thick zone of the Big George Coal Seam. We hypothesize that fresh recharge of nutrient rich water or contributions from thermogenic pathways could be

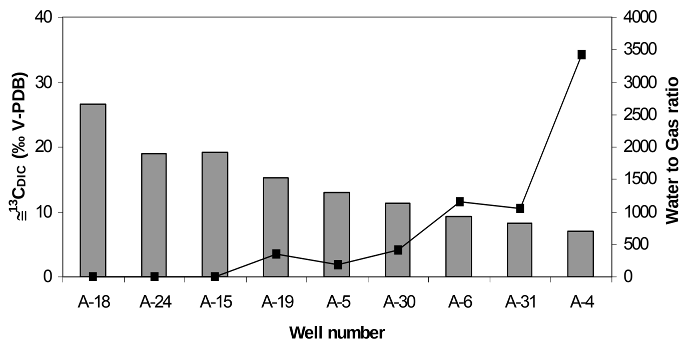


Figure7: The well-head water samples showing low $\delta^{13}C_{DIC}$ values had high water to gas ratio indicating water being withdrawn from overlying and underlying aquifers during de-watering process.

partly responsible for this isotopic excursion. Scott is currently in process of interpreting the data and writing his thesis.

Significance

The results from this project indicate that methanogenic waters in the study area can be distinguished from ambient groundwaters by their higher Na and HCO_3^- , and relatively lower Ca, Mg and SO_4^{2-} concentrations. However, site to site variations in bedrock/soil and water chemical composition results in wide range of values for these parameters limiting their applicability as effective tracers of CBNG co-produced waters. The higher $\delta^{13}C$ of DIC of co-produced CBNG water on the other hand can prove to be an effective tracer to trace seepage out of CBNG water holding impoundments. Preliminary results from water samples collected from well-heads of producing wells in Atlantic Rim and Powder River Basin indicate strong correlations between enriched $\delta^{13}C_{DIC}$ and water to gas ratios. The carbon isotope technique developed by these two projects can potentially help in addressing regulatory issues related to discharge of CBNG co-produced water and also help CBNG operators to maximize gas production while maintaining optimal drilling costs and protecting the valuable groundwater resources of the region.

Student Support Information

Graduate : Josh Baggett MS student in Renewable Resources advised by Dr. Sharma is working on this project for his Masters thesis in Rangeland Ecology and Watershed Management/ Water resources. He received training in taking field water quality measurements, geochemical and isotope sampling protocols, geochemical analysis and stable isotope analysis.

Scott A. Quillinan MS student in Department of Geology and Geophysics co-advised by Drs. Frost and Sharma received training in taking field water quality measurements, geochemical and isotope sampling protocols, geochemical analysis and stable isotope analysis.

Undergraduate : Paul Haselhorst, a Geology major and technician of Dr. Sharma, received training in preparing samples for geochemical and isotopic analysis and also in running samples on the stable isotope ratio mass spectrometer.
Patrick Warden technician of Dr. Sharma and Biology major received training in preparing and running isotopic analysis on water samples.

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Water Quality Criteria for Wyoming Livestock and Wildlife

Basic Information

Title:	Water Quality Criteria for Wyoming Livestock and Wildlife
Project Number:	2008WY44B
Start Date:	3/1/2008
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Water Quality, Water Supply, Agriculture
Descriptors:	None
Principal Investigators:	Merl Raisbeck, Michael A. Smith, Cynthia Tate

Publication

1. Raisbeck, M. F., S. Riker, B. Wise, R. Jackson, 2010. Safety of produced water for livestock and wildlife, In Coalbed Natural Gas: Energy and Environment (ed. Reddy, KJ), Nova Science Publishers, Haupage, NY, pp 81-120.

Water Quality Criteria for Wyoming Livestock and Wildlife

PIs: Merl Raisbeck, Cynthia Tate, and Michael Smith
Collaborator: Jennifer Zygmunt
Progress Report, Year 2 of 3

Abstract

Water is arguably *the* most essential nutrient for terrestrial animals. While most mammals can survive for a week or more without food, 2-3 days without water is invariably fatal. Livestock and wildlife in the arid West are often forced to subsist upon less-than-perfect drinking water such as that produced by oil and gas development ("produced water"). Water quality standards, as enumerated in Wyoming Department of Environmental Quality (WYDEQ) regulations governing surface discharges, are based upon science that is several decades old and have recently been challenged. The fact that the challenges were, themselves, based upon dubious information is in itself a reflection of the generally mediocre state of current water quality recommendations by various public institutions. It is not that the data don't exist, but rather that they haven't been compiled into any sort of useful, user-friendly summary or, in some cases, mineral production has itself created new questions (e.g. chronic toxicity of water-borne barium to ruminants) that never had to be answered before.

Our group recently completed a literature review of several water quality elements important to domestic livestock and large mammalian wildlife for the Wyoming Department of Environmental Quality (Raisbeck *et al.*, 2007). We have received requests for hard copies of this document from as far away as Australia and South Africa. The current project is intended to expand upon the previous effort to include other elements, such as iron and uranium, which are potentially of future interest as they occur naturally in Western waters and are extremely toxic. Coincidentally, this project will provide a MS student and 2-3 undergraduates training in toxicology, risk assessment and water quality - skills which are currently needed in Wyoming.

Methodology

Our methodology is fairly simple, if laborious. Older (roughly pre-1990) reviews are obtained to validate the previous state of the art re: the toxicity of a given element in our species of interest (cattle, sheep, horses, antelope, deer and elk). After these documents are digested, a search is instituted for detailed, primary sources via biological literature databases such as Medline, Biosis and CAB. These papers are reviewed, rated for applicability and reliability and summarized in our database. The better papers are used as a basis for reverse-search strategies such as citation searches. If the amount of information available from conventional sources is inadequate, we contact regional animal health agencies for unpublished data such as diagnostic case reports and game and fish studies.

Each paper is rated for applicability (i.e. route of administration, class, age and species and chemical form of the toxicant typical of what is found in Wyoming) and reliability (adequate controls and sufficient numbers of animals to support conclusions, etc.). Case reports are evaluated upon the basis of similar criteria, as well as whether possible differentials have been ruled out and Koch's postulates have been fulfilled. This process requires some judgment, which is where the expertise of our team comes into play. Controlled experimental studies are normally given more weight than case reports; *however*, an experiment which concludes there is no effect in n=3 animals is less credible than a case report documenting a 5% mortality among 200 head exposed to the same substance and dose. In the absence of good quantitative data in each of the species of interest, we attempt to extrapolate from species for which there are data. Such extrapolations are based upon known comparative physiology of our various species and indicated as such in the final report.

Progress to date

During preceding years, we compiled and prioritized a list of contaminants to review (B, Cd, Cr, Cu, Pb, Hg, Zn, U) in collaboration with the Wyoming DEQ, completed reviews of B and Cd, and started Cr. During the last year we finished up Cr, completed Cu, Pb, Hg and are collecting data for Zn and U. We have so far complied a data base of over a thousand documents, mostly peer-reviewed, pertaining to the project, and believe that we have a good basis of knowledge to base our recommendations upon.

Chromium (Cr) has two main valence states of concern to our project, Cr(III) is the predominant form of Cr found naturally in surface water, with Cr(VI) resulting mainly from human activity. Most sources indicate that relatively large doses of Cr(III) are required for toxicity, but that relatively small doses of Cr(VI) damage multiple organ systems. Due to the lack of adequate scientific experiments into the toxic levels of Cr in the species of interest (much of the data is rodent data) and virtually no data in ruminants (other than a few scattered clinical reports with no dose data) setting a strong recommendation for this contaminant in drinking water was difficult. Based upon the limited toxicity data, it seems likely that the NOAEL level in large ungulates will be less than 10 mg/kg BW but possibly as low as 1 mg/kg BW (extrapolated from rodent data) which would equate to 5 mg Cr/L in drinking water, given our previously stated assumptions.

Copper (Cu) is an essential micronutrient that tends to be of concern for deficiency than toxicity in Wyoming and surrounding states. That said, it is widely accepted that sheep are unusually susceptible to Cu toxicity. This is due to physiological differences (mainly in the excretion of excess Cu) between sheep and other livestock species. There is very little literature regarding Cu toxicity in wild ruminants and horses, despite widespread exposure to livestock mineral products and, due to the lack of even clinical reports of toxicity (the majority of published reports deal with deficiency), we are confident that they are no more susceptible to Cu toxicity than sheep or cattle. Although sheep are the most susceptible species in terms of mg/kg BW, cattle drink more water and thus are exposed to a larger dose at any given Cu concentration. After calculating NOAELs for both species (including common Wyoming forage Cu content) we found surprisingly similar minimum toxic concentrations of Cu in drinking water (4.5 and 4.125 mg Cu/L, for sheep and cattle, respectively). Thus, 4 mg Cu/L represents a maximum tolerable water concentration that would provide protection to the most sensitive species in the most conservative situation (fast growing animal, warm summer temperatures).

There are 3 adverse effects associated with long term lead (Pb) exposure in our species of interest: 1) chronic toxicity as manifested by effects ranging from weight loss to death in adult animals, 2) behavioral effects in neonates exposed *in utero* or shortly after birth, and 3) Pb residues in edible animal products such as milk and meat. Cattle and sheep were once again our most sensitive species of concern. They were also the most widely represented in the literature, allowing for a higher degree of confidence in the recommendations that we are providing. Horse data is highly inconsistent and much of the data that is provided is counter intuitive, with NOAELs and LOAELs varying considerably between studies. In cattle and sheep, the highest NOAELs in the reports reviewed were 2.2 – 4 mg/kg BW and 2.3 mg/kg, respectively. The lowest LOAELs were 5-6 mg/kg BW for cattle and 4.5 mg/kg BW for sheep. Young animals are much more susceptible to Pb toxicity and neurological disorders due to higher permeability of both the gastrointestinal tract and the blood brain barrier, resulting in Pb accumulation in the central nervous system. As far as neurological changes are concerned, it is difficult to put a solid recommendation on subtle neurological endpoints such as IQ (it is difficult to determine at what point such deficits will affect the ability to function) but in one chronic study (60 days), baby calves were poisoned by doses as low as 1 mg/kg BW when administered in whole milk. Transfer of Pb from mother to young occurs at relativly low levels and the vast majority of Pb poisoning cases in young animals is due to ingesting Pb based products (Pb based paint, batteries) and not from water consumption. Lead can accumulate in edible tissues (muscle, liver, kidney) when animals are exposed to increased levels of Pb, but the tissue concentrations begin to decrease with cessation. The FDA has not established fixed action limits for meat, rather dealing with contamination on a case by case basis. The current strategy is to use background levels as reported in Puls (1994) as "acceptable". Using these same target concentrations we calculated drinking water Pb levels below 4.47 mg Pb/L in cattle and 3.21 mg Pb/L in sheep should be safe for consumption.

Mercury (Hg) is found in nature in both the organic and inorganic form. Mercury varies greatly in the absorption, retention and toxicity depending upon the form. The form of most concern to this project is methylmercury (MeHg) due to its high rate of absorption (90-95% of administered dose), long half-life (70 days in mammals) and its ability to penetrate both the placental barrier and the blood brain barrier. The elimination of MeHg is further complicated by the ability of the contaminant to be reabsorbed from the intestine once removed from the liver, a process known as enterohepatic recirculation. MeHg accumulates in all tissues, with the liver and kidney accumulating the highest concentrations, but brain and muscle also retain significant amounts. Cattle seem to be most susceptible to Hg toxicity, especially young animals. Signs of toxicity can vary depending upon the dosage, with long term low dose effects mostly occurring in the proximal tubules of the renal system and at higher doses the toxicity seems to manifest as neurologic disorders. Strong tissues residue standards exist and due to the high rate of accumulation of Hg within edible tissues, water levels will probably be driven more by human dietary levels than animal toxicity. We are currently constructing a biologic transfer model to determine exposure limits based upon food residues, and we recommend that overall exposure be limited to less than 1 mg/L in drinking water for adequate protection from chronic toxicity, but anticipate that a value based upon human residue limits will be considerably lower.

We are currently developing recommendations for Uranium (U). Uranium is a naturally occurring mineral in the region of interest to this project. The great majority (99.28%) of U occurs as the 238 isotope form. Ingested U associates with red blood cells and is transported throughout the body, accumulating in bone and soft tissues (mainly liver and kidney). The majority of circulating U is quickly excreted via urine, with up to 50% of the dose removed within the first hour. The remaining U is either taken up in the bone (roughly 1/3 of any given dose) or deposited in the soft tissues, mainly the kidneys. Due to the route of excretion, U tends to cause renal damage, mainly in the proximal tubules. The biological half life of U (in rodents) is divided into two compartments with bone being between 93-165 days and kidney being between 5 and 11 days. Excessive U exposure also induces an immune response in the host. There is very little, if any, true experimental data on U in our species of interest. The majority of studies have been conducted on rodents. We are working on possible extrapolations from rodent data, but this may not be possible.

Publications/Presentations

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M. F. Raisbeck (2009): Water quality for Wyoming Livestock and Wildlife. CLE, Int'l, Wyoming Water Law, Cheyenne, WY 4/17/09.

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B. Wise, M. Raisbeck (2010) Water quality for Wyoming Livestock and Wildlife. 49th Annual Meeting of the Society of Toxicology, Salt Lake City, UT, 3/15/10.

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Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming II: Further Airborne Cloud Radar and Lidar Measurements

Basic Information

Title:	Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming II: Further Airborne Cloud Radar and Lidar Measurements
Project Number:	2009WY46B
Start Date:	3/1/2009
End Date:	2/29/2012
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Water Quantity, Climatological Processes, Hydrology
Descriptors:	None
Principal Investigators:	Bart Geerts

Publication

1. Geerts, B. and Q. Miao, 2010. Vertically-pointing airborne Doppler radar observations of Kelvin-Helmholtz billows, Monthly Weather Review, 138, 982-986.

Detecting the signature of glaciogenic cloud seeding in orographic snowstorms in Wyoming II: Further airborne cloud radar and lidar measurements

Year 1 report
for a three-year (Mar 2009 – Feb 2012)
U. S. Geological Survey and the Wyoming Water Development Commission grant
Dr. Bart Geerts, PI
4/30/2010

1. Abstract

This proposal (referred to as Cloud Seeding II) called for two research flights of the University of Wyoming King Air (WKA) over the Snowy Range (Medicine Bow) mountains in Wyoming during the time of glaciogenic cloud seeding conducted as part of the five-year Wyoming Weather Modification Pilot Project (WWMPP). This pilot project, administered by WWDC and contracted to the National Center for Atmospheric research (NCAR) and Weather Modification Inc (WMI), involved seeding from a series of silver iodide (AgI) generators located in the Snowy Range. The flights were conducted on 3/25 and 3/30 2009. A previous grant from the UW Office of Water programs, referred to as Cloud Seeding I, supported five WKA flights, flown in Feb 2008 and in Feb-Mar 2009. All seven flights (**Table 1**) were a success in terms of both the target weather conditions and instrument performance.

2. Summary of the field work

All seven flights listed in Table 1 followed the general flight pattern shown in **Fig. 1**. We targeted west- to northwesterly wind, because in such flow the Snowy Range forms the first obstacle following a long fetch over relatively flat terrain (the Red Desert), because three generators (Barret Ridge, Mullison Park, and Turpin Reservoir) are aligned with the cross-wind flight legs (Fig. 1), and because this flow pattern does not interfere with NCAR's randomized experiment. This is because under such flow the seed generators are upwind of both the target and the control snow gauges. Aside from the along-wind leg (whose orientation depends on the prevailing wind, pivoting around GLEES), there are five fixed tracks roughly aligned across the wind. The NW-most of these five tracks is upwind of the three generators, and the 2nd, 3rd, 4th, and 5th tracks are about 2, 6, 9, and 13 km downwind of the generators. The first four legs are on the upwind side, while the 5th one (tracking over GLEES) is mostly on the downwind side.

The pattern shown in Fig. 1 was repeated four times on several flights: the first two patterns had the seed generators off, and the last two patterns were flown with the seed generators on. On other flights we concentrated on the three most-downwind legs, and the number of patterns with seeding was increased at the expense of flight time without seeding (**Table 1**).

On all flights the Wyoming Cloud Radar (WCR) operated flawlessly, with three antennas (up, down, and forward-of-nadir). We recently discovered a small (0.60 m s^{-1}) downward bias in the Doppler vertical velocity from the up-looking antenna, on all flights. This correction was found after extensive comparisons with the down-looking antenna and with flight-level vertical wind data. On all flights we also had the up-looking lidar (Wyoming Cloud Lidar, WCL). On the last four flights, we also collected data from the recently-purchased down-looking lidar.

No less than 4 graduate students participated in the field campaign (see Section 9), although only one graduate student (Yang Yang) is focusing her MSc research on the data from these five flights.

The seven cases have been used to construct composites of radar data and flight-level data, in order to tease out the effect of AgI seeding on cloud processes and snowfall. In all cases the static stability was rather low, and the wind speed strong, such that (a) boundary-layer turbulence effectively mixed tracers over a depth of at least 1 km, and sometimes above flight level (2,000 ft above the Med Bow Peak) up to cloud top, and (b) the Froude number exceeded one and thus the flow went over (rather than around) the mountain range (Table 1).

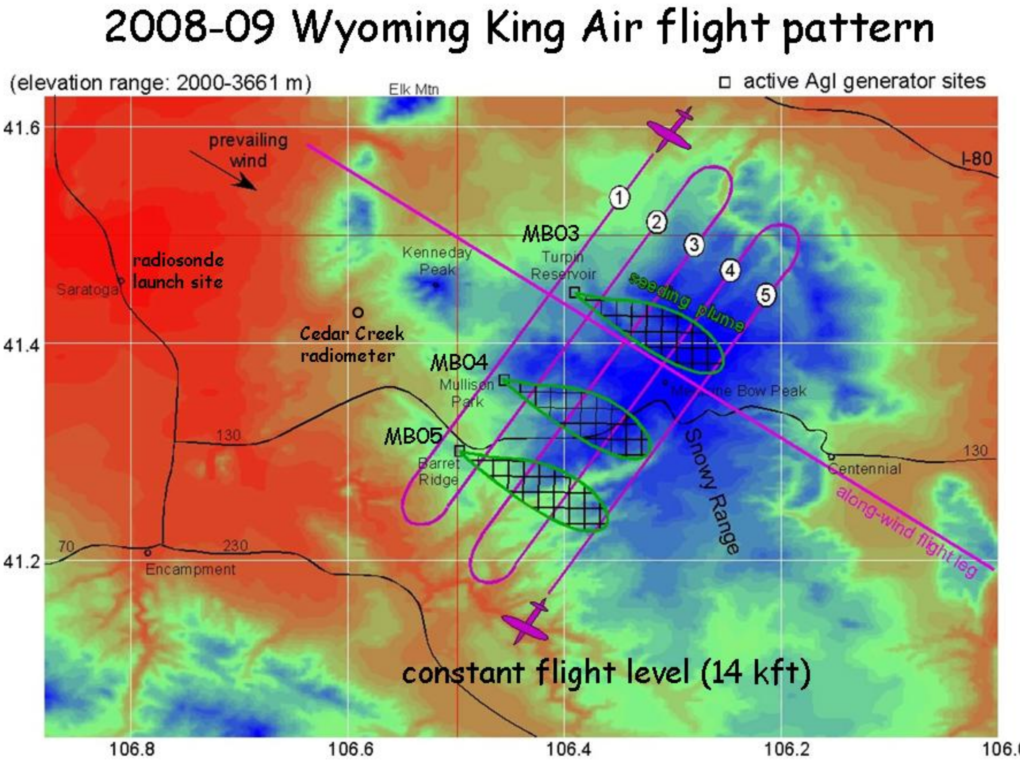

Fig. 1. A schematic of the WKA flight legs in the Snowy Range, over the AgI plumes (shown schematically with a green outline) released from three generators on the ground. The color background field shows the terrain. On all flights the flight level was set at 4,276 m (14,000 ft) MSL. The prevailing wind was from the NW. One flight leg was across the terrain (along the wind), the other 5 flight legs were roughly across the winds at various distances downstream of the three active AgI sources.

3. Objectives and methodology

The key objective is to examine the impact of cloud seeding on radar reflectivity between the AgI generators and the slopes of the target mountain. To do this, a composite of reflectivity for seed and no-seed conditions for all downstream flight legs along the wind needs to be built. And it needs to be ascertained that the observed differences in composites is both statistically significant and not attributable to differences in vertical air velocity.

flight date	**11 Feb 2008**	**25 Feb 2008**	18 Feb 2009	20 Feb 2009	**10 Mar 2009**	**25 Mar 2009**	30 Mar 2009
start times (UTC, hh:mm)							
WKA take-off	**19:41**	**20:05**	16:22	21:30	**13:57**	**15:54**	17:04
Barrett Ridge generator	**21:28**	**21:55**	18:12	23:20	**14:54**	**16:45**	17:54
Mullison Park generator	**na**	**21:56**	18:15	na	**14:52**	**16:43**	17:52
Turpin Reservoir generator	**21:29**	**na**	18:09	23:19	**14:56**	**16:42**	17:50
flight pattern							
no-seeding leg sequence	**54321 54321**	**54321 54321**	54321 54321	54321 54321	**54321**	**54321**	54321
seeding leg sequence	**54321 54321**	**54321 54321**	54321 54321	54321	**5 times 543**	**5 times 543**	4 times 543
no-seed flight-level mean fallspeed (m s^{-1})	**1.19**	**0.99**	0.80	1.04	**0.91**	**1.02**	0.80
seed flight-level mean fallspeed (m s^{-1})	**1.04**	**0.93**	0.70	0.95	**0.78**	**0.80**	0.72
Saratoga sounding data							
mean wind speed (m s^{-1})	**15**	**12**	14	15	**21**	**14**	11
mean wind direction (°)	**317**	**293**	300	293	**272**	**265**	323
Brunt-Väisälä frequency (10^{-2} s^{-1})	**0.51**	**0.15**	0.78	0.76	**0.52**	**0.00**	0.61
Froude number	**1.9**	**5.0**	1.04	1.2	**2.6**	**∞**	1.1
Richardson number	**0.7**	**0.2**	8.1	2.4	**0.4**	**0.0**	3.5
lifting condensation level (m MSL)	**2719**	**2782**	2630	2314	**2896**	**2618**	2807
temperature at generator level (°C)	**-9**	**-7**	-10	-10	**-17**	**-8**	-15

Table 1: Summary of the seven flight days. The flight legs are numbered as shown in Fig. 1. The mean fallspeed of hydrometeors is based on a comparison between the air vertical velocity measured by the gust probe, and the mean WCR particle vertical motion measured at the nearest radar gate above and below the aircraft, at a range of ~120 m. The sounding data come from a radiosonde released upwind of the mountain. The numbers shown in the table represent averages between ground level and the elevation of Medicine Bow Peak. The Brunt-Väisälä frequency *N* is the dry (moist) value below (above) the cloud base. The Froude number is calculated as the wind speed divided by *N* and the height of Medicine Bow Peak above Saratoga. The Richardson number is N^2/S^2, where *S* is the magnitude of the shear between the mixed layer (50 hPa deep) and mountain top level. The elevation of the three generators ranges between 2752-2946 m. The direction normal to the five flight legs is 309°. The mean temperature at the elevation of the generators is estimated from the Saratoga sounding.

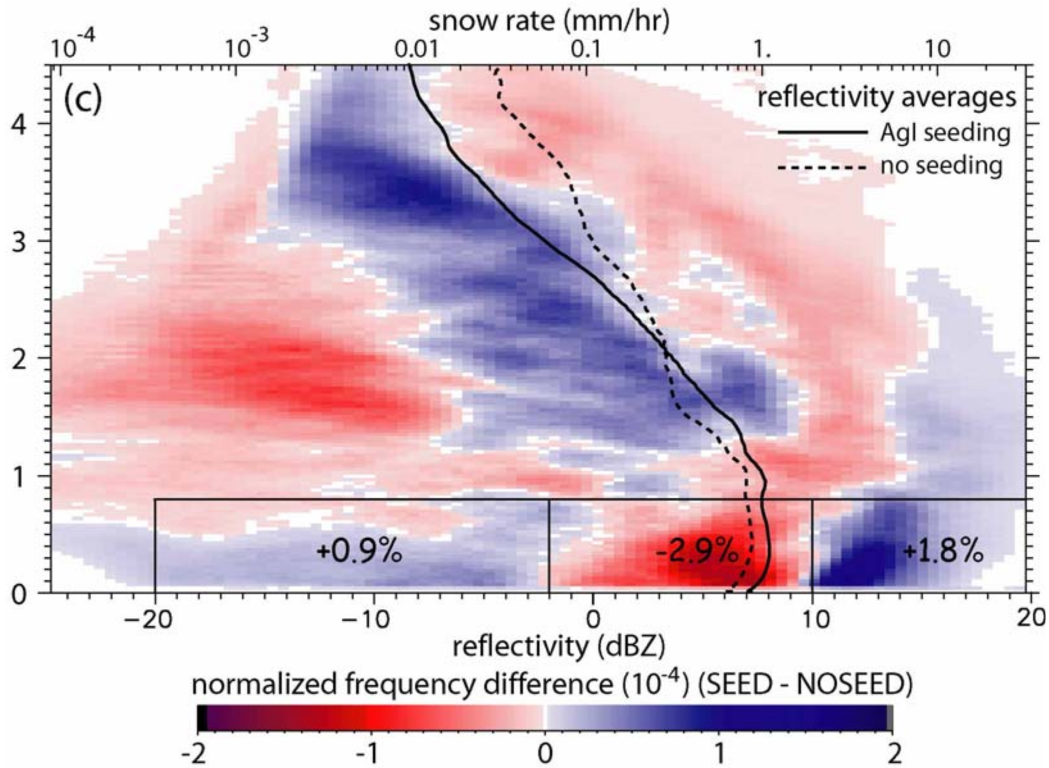

Fig. 2: Normalized frequency by altitude (FAD) of the difference in WCR reflectivity during seed and no-seed conditions. Also shown are cumulative normalized frequency differences (seed minus no-seed) in three boxes near the ground, expressed as a percentage, and the mean reflectivity profile during seed and no-seed conditions. The snow rate (S) shown in the upper abscissa is inferred from S=0.11 $Z^{1.25}$ (Matrosov 2007).

4. Principal findings

In Feb 2010 a paper was submitted to *J. Atmos. Sci*. (Geerts et al. 2010), the most prestigious journal in its field. This paper is still in review, but the reviewers' comments are relatively minor, so we are confident that it will be accepted. In April 2010, Geerts was an invited keynote speaker at the Annual Weather Modification Association meeting in Santa Fe NM. In that talk, he presented the main findings of the *J. Atmos. Sci*. paper.

Our ongoing study provides experimental evidence from vertically-pointing airborne radar data, collected on seven flights (Table 1), that ground-based <u>AgI seeding can significantly increase radar reflectivity within the PBL in shallow orographic snow storms</u>. Theory and a comparison between flight-level snow rate and near-flight-level radar reflectivity indicate <u>a ~25% increase in surface snow rate during seeding</u> (**Fig. 2**), notwithstanding slightly stronger updrafts found on average during no-seeding periods. The partitioning of the dataset based on atmospheric stability and proximity to the generators yields physically meaningful patterns and strengthens the evidence.

Firstly, the AgI seeding signature is stronger and occurs over a greater depth on the less stable days than on the three more stable days. Secondly, it is stronger for the two legs close to the generators than for the two distant legs. A random resampling of all flight passes irrespective of seeding action indicates that the observed enhancement of high reflectivity values (>10 dBZ) in the PBL during AgI seeding has a mere 2.2% probability of being entirely by chance (**Fig. 3**).

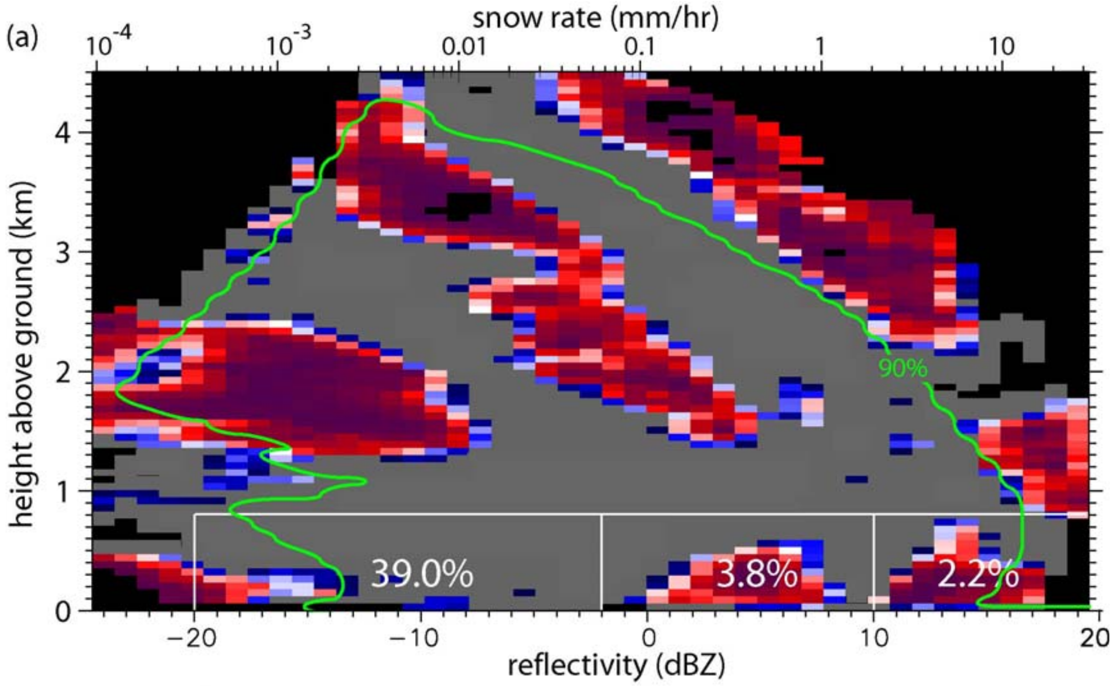

Fig. 3: Percentage of differences between randomly selected subgroups that exceeds the observed seed minus no-seed difference in WCR reflectivity (shown in Fig. 2). The white numbers show the same, not at the bin level but within the same boxes as in Fig. 2. In the grey areas there is a more than 10% probability that the seed minus no-seed difference is by chance. The green contour comprises 90% of the cumulative data frequency.

The results presented have limitations, mainly because just seven storms were sampled and these storms represent a rather narrow region in the spectrum of precipitation systems in terms of stability, wind speed, storm depth and cloud base temperature. While the analysis yields strong evidence for an increase in reflectivity near the surface, the quoted change in snowfall rate (25%) is unlikely to be broadly representative. It appears that PBL turbulence over elevated terrain is important in precipitation growth, both in natural and in seeded conditions, and thus the same results may not be obtained if the precipitation growth primarily occurs in the free troposphere. This work needs to be followed up with a longer field campaign under similar as well as more diverse weather conditions. Such campaign should include ground-based instruments, such as vertically pointing or scanning radars and particle sizing and imaging probes.

5. Further plans

So far we conducted seven flights over the Snowy Range, five funded under Cloud Seeding I and two under this grant (Cloud Seeding II). Following the review of the *J. Atmos Sci.* paper (Geerts et al. 2010), we are preparing a paper dealing with the importance of PBL turbulence on orographic precipitation (Geerts and Miao 2011), and another paper further exploring seeded cloud properties with flight-level data (Yang et al. 2011).

We also have two other orographic precipitation studies planned. First, Dr. Geerts is the PI of the SOLPIN component of the current University of Wyoming NSF EPSCoR proposal, called “Earth System Interactions in Complex Terrain”. The SOLPIN (Simulations and Observations of Land-Precipitation Interactions) component is worth about $6 million, plus $2 million in UW matching. If funded, then both winter and summer orographic precipitation will be studied, using experimental data and numerical simulations.

Second, Dr. Geerts is the PI in a proposal, known as ASCII (AgI Seeding of Cloud Impact Investigation). This proposal in preparation is a collaboration with NCAR, and is to be funded by NSF. If funded, ACII will be conducted in the Medicine Bow Mountains in the winter of 2011-12, as part of the WWMPP. The emphasis here is on the cloud microphysical effects of glaciogenic seeding in cold orographic clouds.

6. Significance

Our findings are believed to be very significant. Geerts was an invited keynote speaker at the Annual Weather Modification Association meeting in Santa Fe NM in April 2010. At that meeting, Arlen Huggins, a veteran researcher in weather modification, mentioned our work as one of the most significant achievements in glaciogenic seeding efficacy research in the past decade.

7. Publications

- Geerts, B. and Q. Miao, 2010: Vertically-pointing airborne Doppler radar observations of Kelvin–Helmholtz billows. *Mon. Wea. Rev.* , **138**, 982–986.
- Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: The impact of glaciogenic cloud seeding on snowfall from winter orographic clouds. *J. Atmos. Sci*., in review.
- Geerts, B., and Q. Miao, 2011: Boundary-layer turbulence and orographic precipitation growth in cold clouds: evidence from vertical-plane airborne radar transects. *Mon. Wea. Rev*., in preparation.
- Yang, Y., B. Geerts and Q. Miao, 2011: The impact of glaciogenic cloud seeding on winter orographic clouds, based on vertically-pointing airborne Doppler radar data and flight-level data. *J. Appl. Meteor. Climat.*, in preparation.

8. Presentations

(a) with abstracts:

- Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: Vertically-pointing airborne radar observations of the impact of glaciogenic cloud seeding on snowfall from orographic clouds. Weather Modification Association meeting, Santa Fe NM, 21-23 April.

(b) without abstracts:

- Geerts, B.: A series of progress reports presented at the Wyoming Cloud Seeding Pilot Project Advisory Team meetings in Cheyenne (Dec 09) or in Lander WY (Jul 09).

9. Students supported

Yang Yang is an MSc student. She joined us from China in August 2008, and was supported by this grant. Her father and grandfather have been involved in cloud seeding research in China, and she has strong credentials, so we are pretty excited to bring her on-board. She is expected to graduate in May 2011.

One post-doctoral scientist, Dr. Qun Miao, has also been partly supported by this grant. He was essential in the data analysis leading to the *J. Atmos. Sci.* paper (Geerts et al. 2010). He left the group in Jan 2010 to assume a faculty position in Ningbo University. He will be back in summer as a visiting research scientist.

Finally, two other PhD students (Yonggang Wang and Mahesh Kovilakam) participated in the field campaign in early 2009. This participation has given them invaluable experience in airborne field research. In fact all four people listed above participated in the flight planning, the flight itself, the flight debriefing and the writing of the flight report.

Effects of Warm CBM Product Water Discharge on Winter Fluvial and Ice Processes in the Powder River Basin

Basic Information

Title:	Effects of Warm CBM Product Water Discharge on Winter Fluvial and Ice Processes in the Powder River Basin
Project Number:	2009WY47B
Start Date:	3/1/2009
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	1
Research Category:	Engineering
Focus Category:	Hydrology, Geomorphological Processes, None
Descriptors:	None
Principal Investigators:	Robert Ettema, Edward Kempema

Publication

1. Ettema, R. and E.W.Kempema, 2010. Ice effects on gravel-bedded channels, (Invited), 7th Gravel-Bedded River Conference, Tadoussac, Quebec, Canada, Sept. 6-10, 22 p.

Effects of Warm CBM Product Water Discharge on Winter Fluvial and Ice Processes in the Powder River Basin

Annual Report, Year 1 of 2

PI: Robert Ettema, College of Engineering, University of Wyoming
Co-PI: Edward Kempema, Geology and Geophysics, University of Wyoming

30 April 2010

Abstract

The purpose of this study is to develop a better understanding of how coal bed methane (CBM) product water heat affects ice formation and winter processes in Powder River Basin streams. Repeat observations were made at three study sites during the 2009-2010 winter season: Prairie Dog Creek at Acme, Powder River at Burger Draw, and Powder River at Beaver Creek. At Prairie Dog Creek, which had no direct CBM input, a typical ice regime existed throughout the winter. In contrast, CBM product water is discharged directly into both Burger Draw and Beaver Creek upstream of their confluences with the Powder River. The warm CBM discharge inhibits ice formation in both of these tributaries except on the coldest nights. In addition, both of these tributaries inject substantial heat into the Powder River. These heat fluxes maintain open water leads (partial channels of open water flow) up to 2.2 km long in the Powder River throughout the winter. The leads are potential sites of nightly frazil and anchor ice formation. However, frazil and anchor ice production was relatively low in these channels, so no major ice jams formed during the winter. Repeated anchor ice formation events could result in increased winter sediment transport.

Objectives

Recovery of coal bed methane (CBM) requires removal of water to depressurize the coal-bed aquifer. In the Powder River Basin (PRB) large amounts of groundwater are removed from coal-bed aquifers during CBM production (Copeland and Ewald, 2008). These CBM produced waters are discharged into surface impoundments, used for irrigation, and discharged directly into perennial and ephemeral streams. In addition to its geochemical load, CBM discharge water carries one more component from coal zones at depth to the surface **–** ***heat***. Rice et al. (2002) note that the average well-head temperature of PRB CBM product water is 20°C. Due to the high specific heat capacity of water, discharge of even small volumes of warm water have potentially large effects on the winter ice regime in rivers. The physical effects of heat discharge (in the form of warm water) into PRB streams are most pronounced in winter, when surface water bodies are normally frozen.

Ironically, injecting heat into a stream may increase ice problems in the stream rather than reduce them. Injected heat impedes formation of a surface ice cover, which most likely will result in persistent zones of frazil and anchor ice formation in PRB streams. Frazil are millimeter-sized discs of ice that form in supercooled, turbulent water. Anchor ice is ice that is anchored or attached to the river bottom. Frazil and anchor ice accumulations can cause rapid local changes in flow conditions resulting in flooding, increased bed and bank scour, and degradation of winter stream habitat. There is a critical need to understand whether and/or how warm CBM product water affects winter fluvial and ice processes in PRB streams, and what effects frazil and anchor ice may have on critical pool habitat for both warm-and cold-water fish species. ***The goal of this study is to develop a better understanding of how CBM product water heat affects ice***

formation and winter processes in PRB streams. The results of this study will be of use to State and Federal planners and managers overseeing CBM production and product water discharge because the project will document how product water heat affects winter processes.

The project's immediate purpose is to determine if and how heat from CBM water discharged into PRB drainages impacts winter flows and ice regimes in PRB streams. Altered regimes can affect winter habitat and channel stability. Initial observations show that ice cover formation is inhibited downstream of CBM discharge points. The lack of a surface ice cover affects other ice processes in the river.

Expected results include:

- An overall evaluation of winter/ice processes in streams receiving CBM produced water;
- Quantitative information including measurements of winter water temperatures along stream reaches with CBM product water discharge;
- Knowledge about frazil and anchor ice formation in Wyoming streams; and,
- Delineation of PRB streams where fisheries may be impacted by changes in wintertime flow and ice regimes.

The results focus on physical processes associated with CBM-water related heat discharge and indicate areas where this discharge could have physical or biological impacts. This focus will provide a better overall understanding of the effects that warm CMB product water discharge may have on winter flow processes and ice formation.

Methodology

In November, 2009 we made two field trips with personnel from the USGS Casper field office. The purpose of these trips was to visit existing research reaches in the PRB and pick sites for detailed studies. We visited a total of 15 USGS gaging station sites and initially chose two sites for detailed study: Prairie Dog Creek at Acme (USGS Site #06306250) and Powder River below Burger Draw (USGS site #440919106091401, Figure 1). A third site, Powder River at Beaver Creek, located about 5km upstream of Burger Draw, was added to the study in February 2010.

Prairie Dog Creek is a small perennial stream with winter flows of about 10cfs ($0.28m^3s^{-1}$). There is no direct discharge of CBM produced water into Prairie Dog Creek. Burger Draw winter flow ranges from 0.5 to 1cfs (0.1 to $0.30m^3s^{-1}$), with the majority of the flow coming from a CBM water discharge point located about 1 km upstream from the Powder River. Beaver Creek has winter flows of 5 to 15cfs (0.14 to $0.43m^3s^{-1}$). Burger Draw and Beaver Creek discharge significant amounts of CBM-produced water into the Powder River. Powder River winter flows range from 34 to 200cfs (1 to $5.7m^3s^{-1}$). Temperature data loggers (Onset Hobo Tidbits) were installed in Prairie Dog Creek, Burger Draw (near the mouth), and the Powder River 140m upstream and 100m downstream of Burger Draw in November 2009. In addition, pressure transducers, used to measure river stage, were placed in Prairie Dog Creek and in the Powder River upstream and downstream of Burger Draw. The pressure transducer above Burger Draw froze before mid-December and was removed. Data loggers were also used to record air temperatures and pressures at both study sites. A Tidbit probe was also placed in Beaver Creek, about 80m above the confluence with the Powder River in February 2010.

These sites were visited a number of times between November 4, 2009 and March 31, 2010. Visits spanned the ice season in the Powder River Basin. The data loggers were serviced on each trip. Ice conditions were also observed and recorded on each trip, and stream discharges were measured. Sites were visited early in the morning so we could look for evidence of frazil and anchor ice formation. If anchor ice was observed, samples were collected for later analysis. The analysis consisted of determining the concentration and size of sediment that was transported by released anchor ice.

Principal Findings

Prairie Dog Creek ice formed in early November and melted in mid-March. The ice cover, which grew to a maximum thickness in excess of 30cm (c. 1ft), remained attached to the stream banks throughout the winter. There was some flooding of the ice surface in December 2009 and March 2010. Also, frazil and anchor ice formed during these periods. The released anchor ice transported sand-sized sediment downstream. Once a solid ice cover formed, water temperatures stabilized at the freezing point throughout the winter. As noted above, there is no direct CBM product water discharge into Prairie Dog Creek. There are multiple CBM-water storage basins in the Prairie Dog Creek drainage, but there is no evidence that they are introducing enough seepage water into the Creek to have any effect on winter ice processes.

Powder River, Burger Draw, and Beaver Creek. Burger Draw and Beaver Creek contained sufficiently high fractions of warm CBM product water that they do not form a permanent ice cover over their entire reaches during the winter. The temperature of Burger Draw water near the mouth cools significantly from its initial ~20°C temperature at the discharge point 1km upstream (Figure 2). Water temperature also varied by several degrees with varying levels of insolation and air temperature throughout the day. These streams formed a thin surface ice cover on the coldest nights (e.g. February 8-9, Figure 2), but this ice melted when the streams warmed during the day. Even though these streams remain open all winter, we saw no evidence that either stream produces any significant amount of frazil or anchor ice.

The Powder River below Burger Draw and Beaver Creek received direct injections of warm, CBM-produced water continuously throughout the winter. These warm water injections significantly affected the Powder River ice regime below the confluences with these two streams. The most visible effect of the warm stream water on the Powder River was the maintenance of open leads (long strips of water channel) below the confluences with these streams throughout the winter. Below Burger Draw, the open water channel was 6 to 10m wide and extended downstream for up to 1.2km from the confluence (Figure 3). This channel, which hugged the right side of the river, was remarkably consistent in shape through the entire winter. The open water channel below Beaver Creek extended 2.2km downstream, and varied from 10m wide to the entire width of the channel (about 30m) in February 2010.

Figure 4 shows temperature data for Burger Draw near the confluence and the Powder River above and below the confluence for the period of February 3-4, 2010. Burger Draw discharge on February 4, measured by the USGS, was 0.52cfs ($0.015m^3s^{-1}$), while the Powder River discharge was 115cfs ($3.3m^3s^{-1}$). When Burger Draw water warmed during mornings, the heat signature is visible as a ~0.1°C "bump" in the Powder River downstream temperature record, located 100m downstream of the confluence. This temperature increase is not seen in the upstream record (Figure 4). Using the discharge and temperature records for February 4, it is possible to calculate the entire CBM-related heat flux from Burger Draw to the Powder River. The amount of CBM-produced heat injected into the Powder River by Burger Draw on February 4 is enough to melt $90m^3$ of ice. Or, more correctly, the heat injected into the River on the 4^{th} was enough to inhibit the formation of $90m^3$ of ice. This was enough heat to maintain the open water channel.

Figure 2, a month long time series of Burger Draw water, Powder River water, and local air temperatures, shows that conditions on February 4 were typical for the entire winter. Burger Draw water temperatures vary by several degrees on a daily basis, but, on average, daily injected enough heat into the river to maintain a long, ice-free, open water channel.

Released anchor ice masses were observed in the open-water leads below the Burger Draw and Beaver Creek confluences every morning when air temperatures were sub-freezing. This released anchor ice contained entrained sediment (Figure 5); sediment concentrations in Powder River anchor ice samples ranged from 0.19 to $37gl^{-1}$. Sediment samples were predominately sand, though pebbles were common. Although anchor ice was common, it did not appear that large enough volumes of anchor ice formed to create any significant channel reduction or ice jamming in the river. Unfortunately, we did not make enough observations of anchor ice formation and ice rafting to draw any firm conclusions about the effects of anchor ice on the overall sediment budget in the stream.

Significance

The results of this first year of study show that direct discharge of CBM product water into the Powder River via tributary streams directly affects the river's winter ice regime by maintaining long open-water leads throughout the winter. The leads are sites of repeated, nightly frazil and anchor ice formation events throughout the winter. Repeated anchor ice formation and release enhance sediment transport throughout the winter. It is also possible that maintenance of an open water channel downstream of CBM injection points may exert slight local effects on channel morphology.

Based on what we learned in the 2009-2010 winter, we plan to direct the Project's second year toward further investigation of the Burger Draw and Beaver Creek study reaches. We will focus on the relationship between CBM heat flux and open-water lead maintenance, local channel morphology, and the effects of anchor ice formation on local sediment transport. Scope exists for a preliminary examination of variations in benthic conditions in reaches of the Powder River subject to the formation of open-water leads.

Publications

Kempema, E.W. and Ettema, R., (accepted), Anchor ice rafting: observations from the Laramie River, Wyoming; River Research and Applications, 15p.

Ettema, R. and Kempema, E.W., (invited), Ice effects on gravel-bedded channels, 7th Gravel-Bedded River Conference 2010, Tadoussac, Quebec, Canada, September 6-10 2010, 22 p.

Presentations

Kempema, E.W. and Ettema, R. November 2010. Progress Report to the Wyoming Water Development Commision, Cheyenne, WY.

Stiver, Jared, March 5, 2010. Effects of CBM waters in the Powder River Basin, invited presentation to RNEW 5710 class taught by Dr. KJ Reddy.

Kempema, E.W., Ettema, R, and Stiver, J. May 25, 2010. Effects of Coalbed Methane Product Water on Winter Flow in the Powder River; Energy Resources and Produced Waters Conference:

Student Support

This project has supported one Civil Engineering student, Jared Stiver, during the past year. Mr. Stiver worked on this project as an undergraduate during the Fall 2009 semester. In January 2009, Mr. Stiver enrolled as a graduate student in Civil Engineering. He will use data from this study for his Master's thesis.

Acknowledgements

We would like to thank the people in the USGS Casper field office for taking the time to show us around the Powder River Basin, for suggesting possible study sites, for supplying historical data, and for answering our many questions. Special kudos to Ray Woodruff, Eric Blajszczak, Jake Neumiller, Jason Swanson, and Karen Watson. The field work would not have been possible without permission from the landowners to access the sites, including Anadarko, Mr. Tom Harriet, Mrs. Shirley Trembath, and Decker Coal.

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COPELAND, D.A., and EWALD, M.L., 2008, Water Associated with Coal Beds in Wyoming's Powder River Basin: Geology, Hydrology, and Water Quality, Wyoming State Geological Survey Exploration Memoir No. 2.: Laramie, WY, Wyoming State Geological Survey, 344 p.

RICE, C.A., BARTOS, T.T., and ELLIS, M.S., 2002, Chemical and isotopic composition of water in the Fort Union and Wastch Members formations of the Powder River Basin, Wyoming and Montana: Implications for coalbed methane development, Coalbed Methane in North America II, The Rocky Mountain Association of Geologists, p. 53-70.

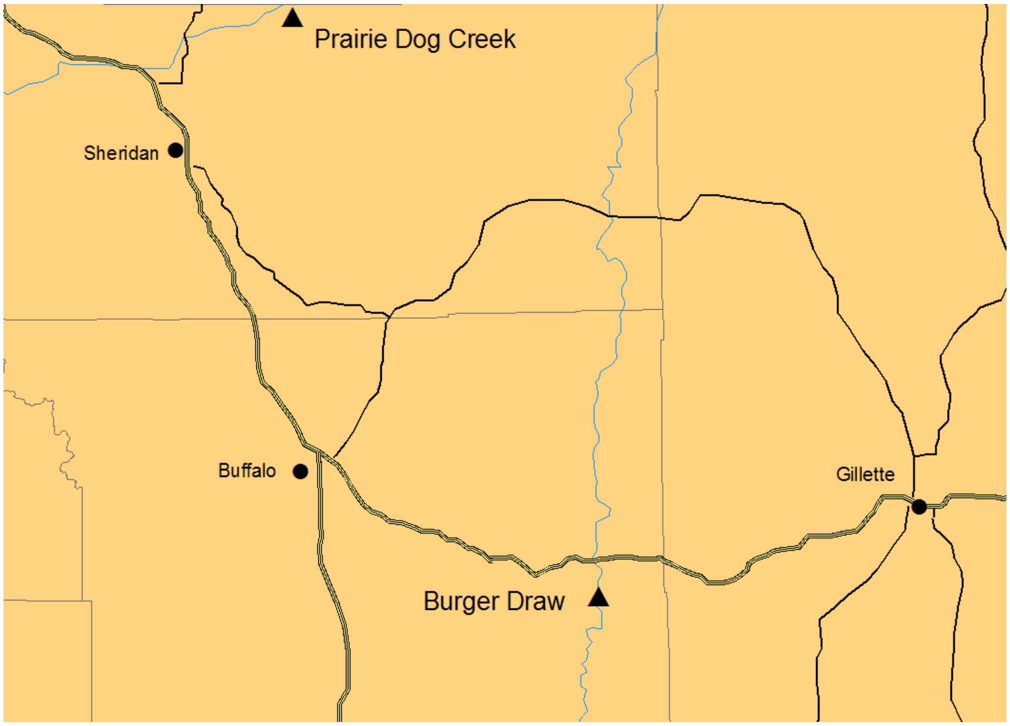

Figure 1. Sites of detailed winter observations (triangles) in the Powder River Basin.

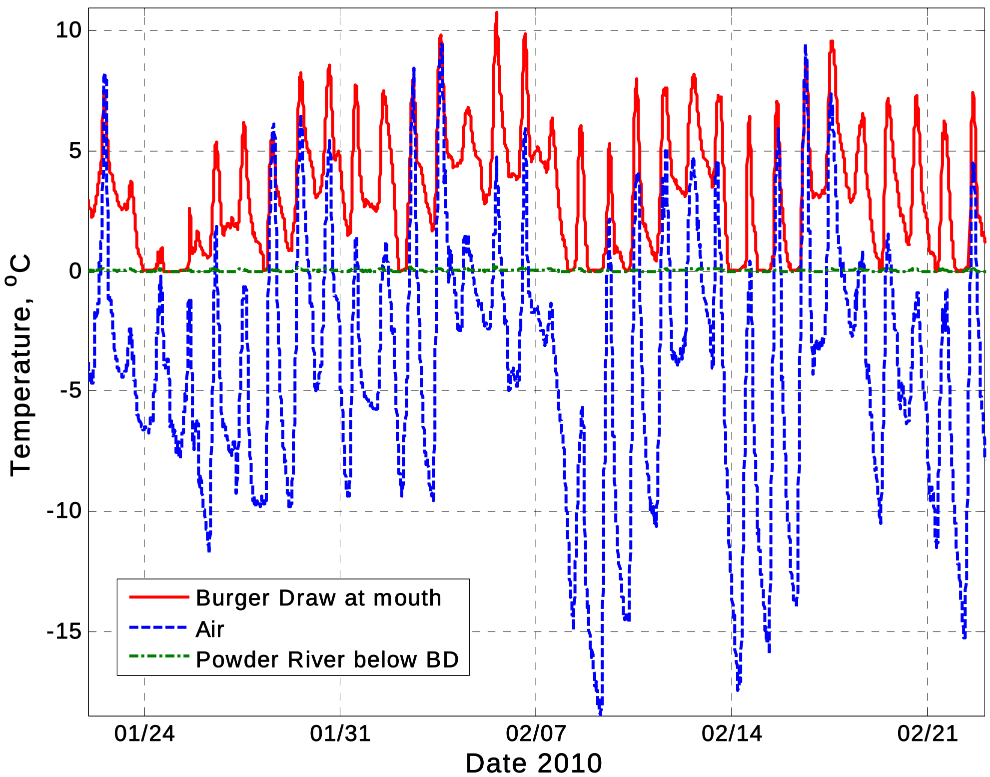

Figure 2. Air and water temperatures for Burger Draw and the Powder River in early 2010. Water temperatures at this site, located 40 m from the confluence with the Powder River, reach the freezing point only during the coldest weather events (e.g. February 8-9). During the day, water temperatures rise to several degrees above freezing even when air temperatures do not.

Figure 3. Open water lead in the Powder River below Burger Draw, February 9, 2010. The 6-10m-wide lead extends 1km downstream of the mouth of Burger Draw, which is immediately behind the photographer.

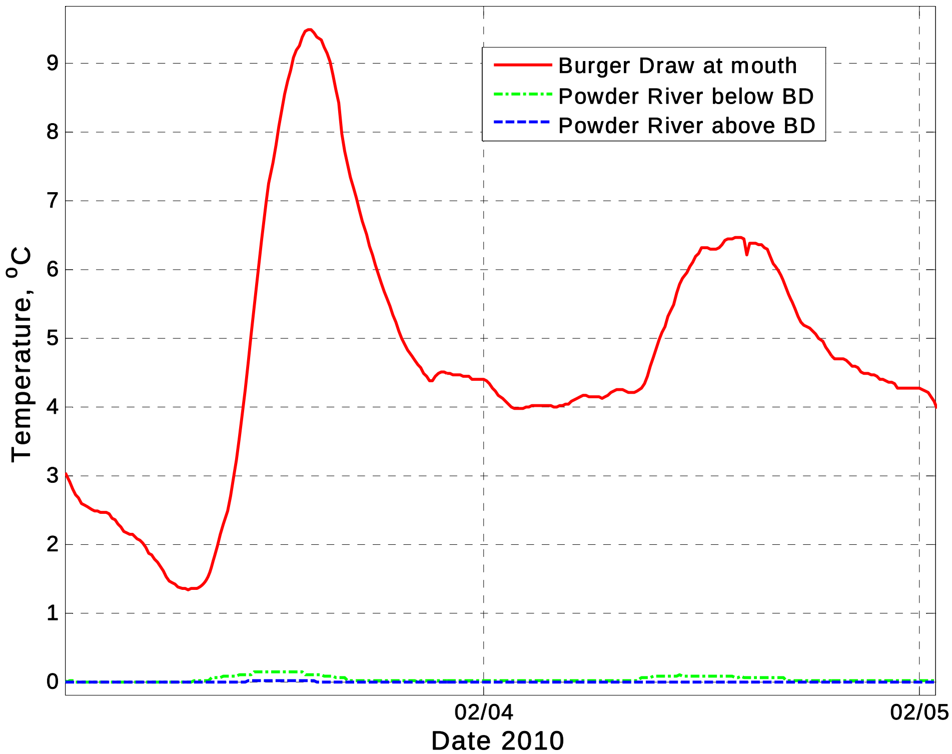

Figure 4. Water temperatures at the mouth of Burger Draw, the Powder River 140m upstream of Burger Draw, and the Powder River 100m downstream of Burger Draw. The majority of the flow in Burger Draw enters the stream at a CBM discharge point 1km upstream of this temperature measurement site near the Draw mouth. The water temperature at the discharge point is about 20°C; it cools significantly on the transect to the Powder River. The warmest daytime water warms the Powder River downstream of the rivers' confluence, as seen by the ~0.1°C rise in water temperatures seen in the river below Burger Draw around midday. This heat maintains the open-water channel below the confluence. On February 4, Burger Draw delivered enough heat to the Powder River to inhibit the formation of 90m^3 of ice.

A

B

Figure 5. A. Released, floating anchor ice in the Powder River below Beaver Creek on 2/9/2010. The open-water sub-channel is 5m wide; the largest, floating anchor ice masses are 1m in diameter. B. Close up of released, floating Powder River anchor ice on 2/9/2010. The sediment in the released anchor ice was predominately sand and gravel. Sediment concentrations in released anchor ice samples reached $37gl^{-1}$.

Characterization of Algal Blooms Affecting Wyoming Irrigation Infrastructure: Microbiological Groundwork for Effective Management

Basic Information

Title:	Characterization of Algal Blooms Affecting Wyoming Irrigation Infrastructure: Microbiological Groundwork for Effective Management
Project Number:	2009WY48B
Start Date:	3/1/2009
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	1
Research Category:	Biological Sciences
Focus Category:	Ecology, Management and Planning, Water Quality
Descriptors:	None
Principal Investigators:	Naomi Ward, Blaire Steven

Publications

There are no publications.

Characterization of Algal Blooms Affecting Wyoming Irrigation Infrastructure: Microbiological Groundwork for Effective Management

PIs: Naomi Ward and Blaire Steven, Department of Molecular Biology, University of Wyoming
Annual Report, Year 1 of 2
Project Duration: 03/01/2009-02/28/2011

Abstract:
Eutrophication, resulting from increased nutrient input into a water body, is one of the most pervasive water quality problems in the United States, affecting lakes, estuaries, streams, and wetlands. Eutrophication is often driven by human activities such as agriculture, where fertilizer run-off and soil erosion are major sources of the nutrient load. The effects of eutrophication include algal/cyanobacteria blooms, leading to hypoxia of the water column and subsequent decline in submerged vegetation, and fish kills. Locally, management of algal blooms represents a significant cost to maintaining the irrigation infrastructure in Wyoming. The effectiveness and environmental impact of these algae treatment strategies are not well understood. It is very difficult to estimate or monitor the total amount of algaecides released into the environment, and the full range of species affected remains unknown. Development of more effective algae treatment strategies is hampered by a *knowledge gap*: we have not identified the key algal and bacterial species and processes involved in establishing, maintaining, and degrading algal blooms in Wyoming lakes. *We are working to address this knowledge gap and thus provide a sound microbiological foundation for long-term development of more targeted, effective algae treatment strategies*. In order to achieve this objective, we are (1) Characterizing algae/cyanobacteria species responsible for blooms, (2) Characterizing the role of bloom-associated bacteria, and (3) Developing model systems to test bacterial/algal interactions. Our long-term goal is to anticipate the type and severity of the bloom and propose predictive management strategies (as opposed to the reactive treatment protocols currently employed).

Objectives:
(1) Characterize algae/cyanobacteria species responsible for blooms,
(2) Characterize the role of bloom-associated bacteria, and
(3) Develop model systems to test bacterial/algal interactions.

Methodology:

A. Field Work. We are working at two sites: Labonte Lake in Laramie (impacted urban lake), and Rock Lake (impacted agricultural lake). Sample types include the lake sediment, water column, and any macroscopically observed algal bloom material. Samples have been subdivided for water quality analysis, microscopy, and DNA extraction.

B. Laboratory Work. Water quality analyses include total nitrogen, total phosphorus, dissolved oxygen, and dissolved organic carbon (DOC). Phase-contrast light microscopy is being used to monitor the development of blooms. Profiling of the microbial community is being performed by ribosomal RNA gene 454 FLX pyrosequencing. Sequencing is being performed by Research and Testing Laboratories LLC (Lubbock, TX). We are performing separate analyses of bacterial, archaeal, and algal populations. Small-subunit (16S) rRNA genes are being analyzed for Bacteria and Archaea, and large-subunit (23S) rRNA genes for algae. This very large amount of sequencing is achieved by multiplexing the 454 runs with the use of bar-coded PCR primers. We are able to simultaneously sequence 16S/23S rRNA genes from all samples on a PicoTiter plate, yielding approximately 5,000 sequence reads per sample. Low-quality sequences are removed and primer sequences trimmed and de-coded using in-house Perl scripts. DOTUR is used to assign sequences to OTUs (Operational Taxonomic Units) at 96% identity, then one sequence representing each of the resulting OTUs is selected for inclusion in a multiple sequence alignment from which a phylogenetic tree is constructed (RaxML). This tree is used to cluster the samples with UniFrac. BLAT, the BLAST-like alignment tool, is used to compare sequences against sequence databases obtained from one of the publicly available rRNA sequence resources. Matches with weak homologies are filtered out, and then each read assigned to a specific taxonomic group, resulting in a weighted phylogeny.

Algal microcosms will be established in Year 2 to study specific interactions between algae and bacteria under controlled conditions. Molecular characterization of the interactions will be performed by 16S/23S rRNA sequencing as described above for the lake samples. Two microcosm types will be set up: one in which we simulate a eutrophication event by addition of extra nitrogen and phosphorus, and a control untreated microcosm. We anticipate running the microcosms in triplicate for 4 weeks and sampling weekly, resulting in 24 samples on which pyrosequencing will be performed. Comparison of the lake and microcosm data will allow us to determine whether the algal-bacterial interactions observed in our microcosms reflect the natural relationships occurring in the lake.

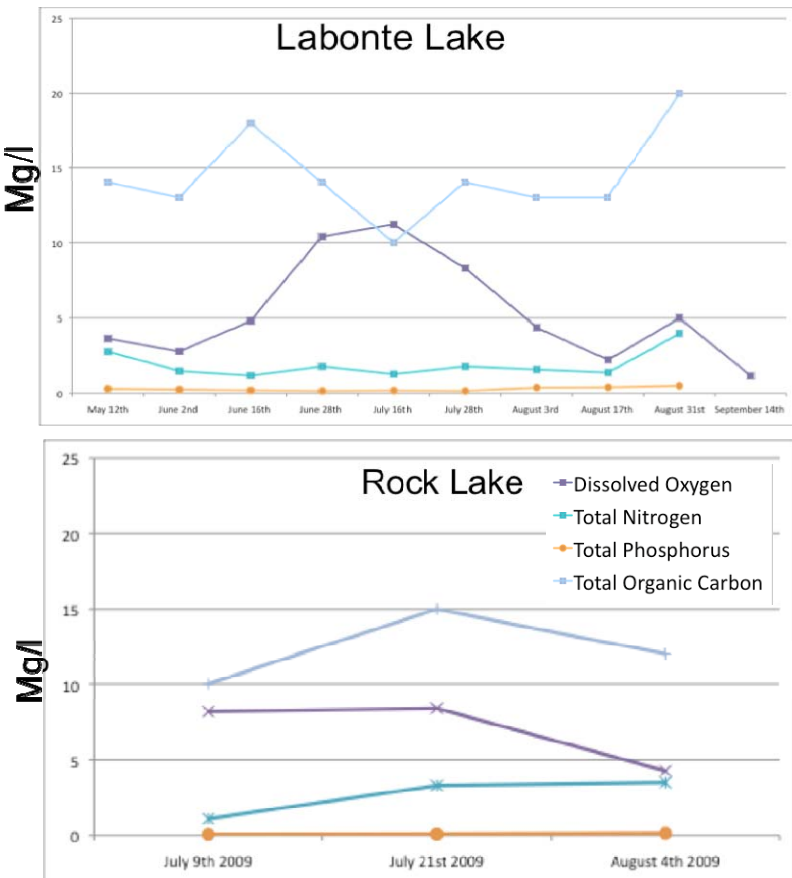

Fig. 1 2009 Water quality analysis data from LaBonte Lake and Rock Lake

Principal Findings:

We have collected samples over the course of 2009 bloom development and collapse in Labonte Lake. This has involved monthly sampling in May and October, with bimonthly sampling during the intervening 4 months, resulting in a total of 10 time points. We also collected peak bloom samples from Rock Lake. Analysis of water quality (Fig. 1) in LaBonte Lake indicated that dissolved oxygen increased until peak algal bloom (mid July), and then decreased during bloom decay. Total organic carbon displayed an inverse relationship to dissolved oxygen, while total nitrogen and phosphorus exhibited smaller fluctuations. Water quality data for samples taken at Rock Lake at peak bloom (mid July to early August) fairly closely resembled LaBonte Lake data from the same time period.

We have generated 141,155 bacterial 16S rDNA sequences, and 133,371 algae 23S rDNA plastid sequences. Archaeal 16S rDNA sequencing is still underway. We are currently engaged in determining the taxonomic affiliation of these sequences, a computationally intensive task that will probably require another three months of work. Preliminary results from analysis of the bacterial sequences in Labonte Lake (Fig. 2, below) suggest that microbial community composition varies dramatically across the bloom season, more obviously in the water column (0.22um and 0.45um filtered water) and algal mat samples than in the sediment. Particularly dramatic fluctuations were observed for the cyanobacteria, betaproteobacteria, gammaproteobacteria, and actinobacteria in the water column and for the cyanobacteria in the algal mat material. Given our long-term goal of using these data for more effective management of algal blooms, we are particularly interested in the populations that increase prior to a bloom (eg actinobacteria in the 0.22um filtered water) and may be contributing to conditions favorable to algal bloom development. Likewise, we will pursue a focus on organisms that increase post-bloom (e.g. betaproteobacteria and gammaproteobacteria in the 0.45um filtered water), and may contribute to algal bloom decline.

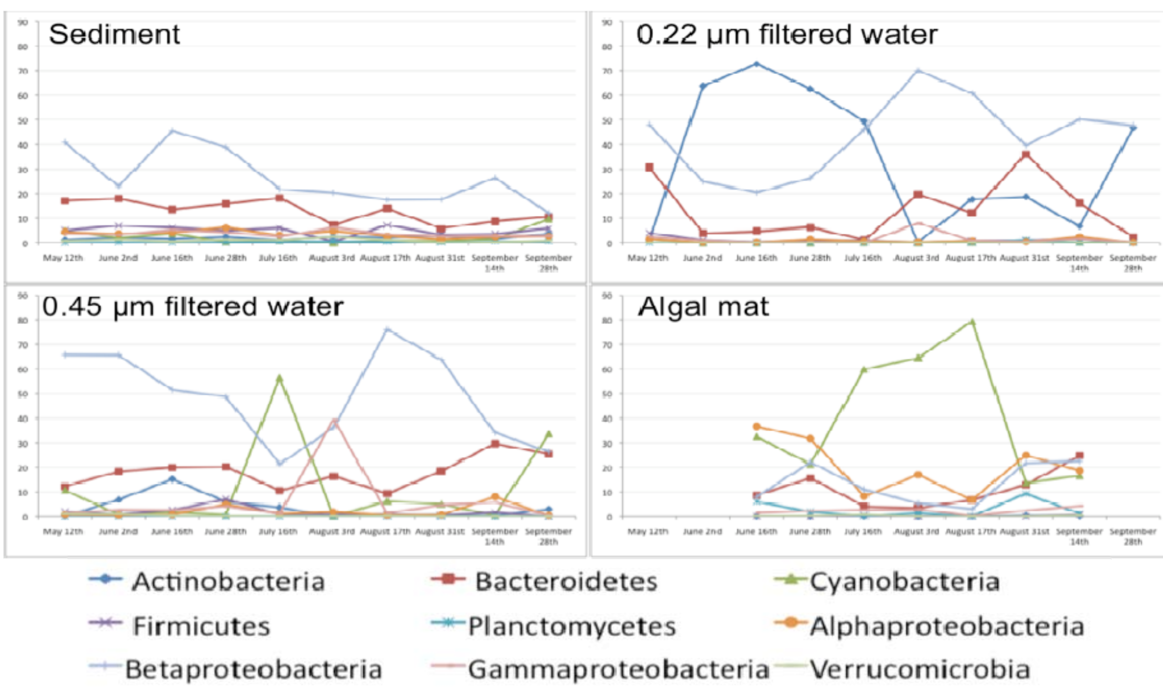

Figure 2. Microbial community composition of sediment, water column, and algal mat samples taken from LaBonte Lake over the course of an algal bloom in 2009. Community composition is measured at the highest taxonomic level for bacteria, the phylum.

Comparison of community composition from LaBonte Lake and Rock Lake sampled at the same time (peak bloom) revealed that while water column and sediment communities were very different, the composition of the algal mat material was remarkably similar at the phylum level (Fig. 3). We will further analyze these data at lower taxonomic levels to see whether the two lakes differ. If the similarity holds, this may be important to confirm in future years and may have implications for management decisions. Remaining work includes the use of sequence data to design taxon-specific FISH probes, 2010 sampling of both lakes, monitoring of 2010 population dynamics by FISH, isolation of algae-associated bacteria, and manipulation of algal microcosms.

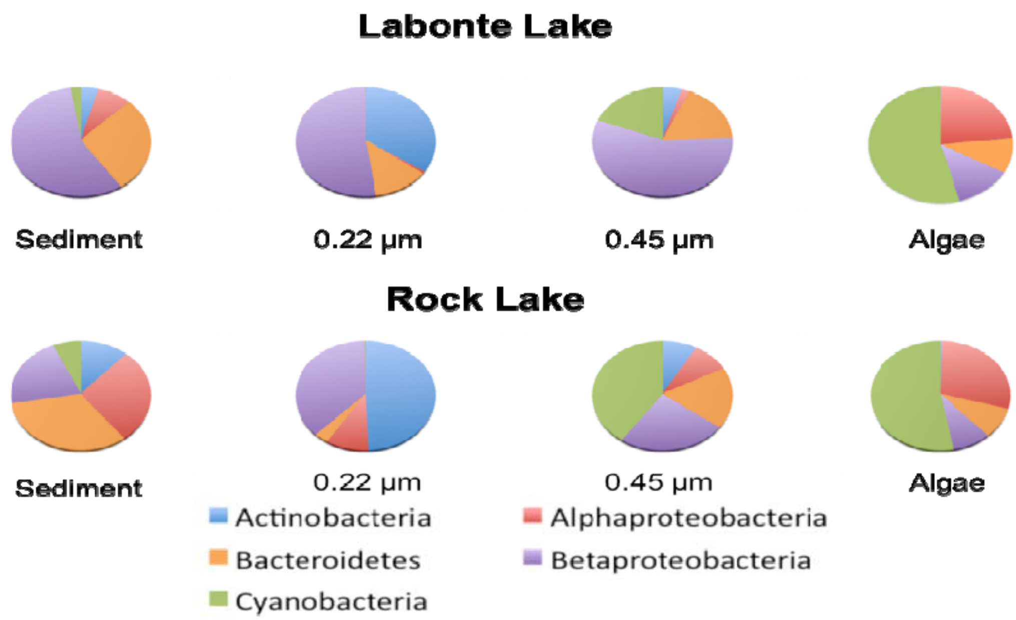

Figure 3. Comparison of microbial community composition of LaBonte Lake and Rock Lake peak bloom samples

Significance:
The microbial community sequencing performed in our project will result in the most exhaustive description of the bacterial community in a eutrophic lake performed to date. It will provide an excellent foundation for selection of bacterial species and functions most relevant to bacteria-algal interactions, for further study. Lastly, it will serve as a reference point for future comparison of microbial communities associated with algal blooms in other lakes. Such comparative analysis will be important to future determination of the most effective management strategies that can be applied in lakes and reservoirs where algal blooms adversely affect irrigation.

Student support:

Undergraduate researcher Sage McCann was supported and trained by this project during the summer of 2009. He is also included as a co-author on an abstract submitted to this year's International Symposium on Microbial Ecology, to take place in August (see below). Sage (graduated Spring 2009, Molecular Biology) was previously an INBRE Transition Scholar, i.e. a Wyoming community college student supported by NIH INBRE funds to participate in research after transfer to UW. Therefore WRP support for Sage allowed further research training for a community college transfer student. Sage is currently pursuing graduate studies in Pharmacy at UW. An additional student (Kristie Capson, Molecular Biology) will be supported in Summer 2010. Postdoctoral fellow Blaire Steven has also received training for the duration of the project.

Publications (student names underlined):

1. Steven, B., S. E. Dowd, K. H. Schulmeyer, and N. L. Ward. Diversity and abundance of planctomycete populations associated with an algal bloom in a eutrophic lake. Under review at Applied and Environmental Microbiology (American Society for Microbiology).
2. Steven, B. and N. L. Ward. Pyrosequencing-based characterization of bacterial, archaeal, and algal population dynamics in a freshwater algal bloom. In preparation for The ISME Journal (Nature Publishing Group).

Presentations (student names underlined):

1. Steven, B., and N. Ward. Deep sequencing of ribosomal RNA genes during an algal bloom in a eutrophic lake: a primer for metagenomic sequencing. DOE Joint Genome Institute 5th Annual User Meeting: Genomics of Energy & Environment. Walnut Creek, CA. March 24-26, 2010.
2. Steven, B., S. McCann, K. H. Schulmeyer, and N. L. Ward. Characterization of the microbial diversity associated with algal blooms in a eutrophic freshwater lake. Abstract submitted to 13th International Symposium on Microbial Ecology. Seattle, WA. August 22-27, 2010.

Information Transfer Program Introduction

During FY09, information dissemination efforts included reports and presentations by the Director to State and Federal entities and the Private sector. The Director reports annually to the Wyoming Water Development Commission and to the Select Water Committee (of the Wyoming Legislature). Presentations were given throughout the state concerning the research program and project results. The Director serves as the University of Wyoming Advisor to the Wyoming Water Development Commission and attends their monthly meetings. This provides a means for coordinating between University researchers and Agency personnel. The Director also serves as an advisor to the Wyoming Water Association (www.wyomingwater.org) and regularly attends meetings of the Wyoming State Water Forum.

Publications and other information dissemination efforts were reported by the PIs of the projects funded under this program. The project PIs report to the Institute s Advisory Committee on an annual basis. Presentations discussing final results are made by PIs of projects which were completed during the year at the Committee s July meeting. Presentations discussing interim results are made by PIs of continuing projects at the Committee s fall/winter meeting. PIs are encouraged to publish in peer reviewed journals as well as participate in state-wide water related meetings and conferences. Publications are listed in the individual research reports.

Director information dissemination FY09 activities included the following:

Director FY09 Service: (1) Wyoming Water Association Board Meeting (Advisor), Cheyenne, WY., January 21, 2009. (2) Wyoming State Legislature, Agriculture Committee. Wyoming Water Development Commission, Omnibus Water Plan. State Capital Bld., Cheyenne, WY., January 27, 2009. (3) Wyoming Water Association Board Meeting, Legislative Update, (Advisor), Cheyenne, WY., January 28, 2009. (4) Wyoming Engineering Society, 89th Annual Convention, Casper, WY., February 5 and 6, 2009. (5) The National Institutes for Water Resources (NIWR) annual meetings. Washington, DC., February 23-25, 2009. (6) Wyoming Water Development Commission workshop-program selection criteria. Cheyenne, WY., March 5- 6, 2009. (7) Wyoming Weather Modification Coordination Meeting. Laramie, WY., April 15, 2009. (8) Sponsor, UW Water Instructors for the 7th Annual Conference, Wyoming Water Law, with CLE International. Cheyenne, WY., April 16-17, 2009. (9) Sponsored and Attended four UW Students for Water Research presentations at the 2009 AWRA Spring Specialty Conference, Managing Water Resources and Development in a Changing Climate, Anchorage, AK., May 4-7, 2009. (10) Wyoming Water Development Commission meeting, Cheyenne, WY., May 6-8, 2009. (11) Wyoming Water Association Committee meeting, Cheyenne, WY., May 14, 2009. (12) Wyoming Water Development Commission Workshop. Cheyenne, WY., June 3, 2009. (13) Wyoming Water Development Commission/Select Water Committee Meeting. Cheyenne, WY., June 4, 2009. (14) Wyoming Water Association Board Meeting/Summer Tour, (Advisor). Thermopolis, WY., July 14-15, 2009. (15) Sponsor: Federal, State, and University Weather Modification Science Rountable meeting. Lander, WY., July 20, 2009. (16) Wyoming Weather Modification Technical Advisory Team Meeting. Lander, WY., July - 21, (17) UW Water Research Program. WRP Priority and Selection Committee meeting to select research priorities. Cheyenne, WY., July 23, 2009. (18) Wyoming Water Development Commission/Select Water Committee joint workshop. Casper, WY., August 19, 2009. (19) Wyoming Water Development Commission/Select Water Committee joint meeting/summer tour. Alpine, WY., August 20 - 21, 2009. (20) Wyoming Water Association Board Meeting (Advisor), Sheridan, WY., October 27, 2009. (21) Wyoming Water Association & Upper Missouri Water Association, Annual Meeting & Educational Seminar. Sheridan, WY., October 28 -30, 2009. (22) Wyoming Weather Modification 2009-2010 Pre-project Ground School. Laramie, WY., November 12, 2009. (23) 64th Annual Wyoming Association of Conservation Districts Convention, Partners in Resource Management, Cheyenne, WY., November 18 - 19, 2009. (24) UW Water Research Program Meeting. WRP Priority and Selection Committee to select research projects. Cheyenne, WY., November 20, 2009. (25) State Engineer's office, development of scope of work on Consumptive Water Use study for the State of Wyoming. Cheyenne, WY., December 11, 2009.

Director FY09 Presentations: (1) Wyoming Weather Modification Technical Advisory Team Meeting. Presentation on Wind River Glacier Study, Cheyenne, WY., February 21, 2009. (2) Fifteenth ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, North Platte River, Wyoming, Streamflow Forecasting. Paris, France, June 28-July 1, 2009. (3) UW-NPS Lectures Series Presentation, Teton and Wind River Glacier Studies. Kelly, WY., July 16, 2009. (4) Wyoming Water Forum, Presentation on Water Research Program Request for Proposals. Cheyenne, WY., September 1, 2009. (5) North American Interstate Weather Modification Council annual meeting. Presentation on Water Research Program involvement in Weather Modification. Jackson Hole, WY., September 30 thru November 2, 2009. (6) Wyoming Water Development Commission meeting, establish recommendations to State Legislature for Biennial funding for Office of Water Programs and FY2010 funding for Water Research Program. Cheyenne, WY., October 7, 2009. (7) Wyoming Water Association & Upper Missouri Water Association, Annual Meeting & Educational Seminar, Presentation on Wind River Glaciers/Streamflow Impacts. Sheridan, WY., October 28, 2009. (8) Wyoming Water Development Commission/Select Water Committee workshop. Presentation on the Wind River Glaciers, Level I Study. Casper, WY., November 4 - 6, 2009. (9) Wyoming Water Development Commission/Select Water Committee joint workshop. Presentation on the UW Office of Water Programs and Water Research Program. Casper, WY., November 4 - 6, 2009. (10) American Geophysical Union fall meeting. Presentation on Glacier Variability in Wyomings Wind River Range and Teton Range. San Francisco, CA., December 14 -18, 2009.

FY09 Information dissemination activities reported by research project PIs include the following:

Project 2007WY39B: Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming Using the Wyoming Cloud Radar. (1) Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: Vertically-pointing airborne radar observations of the impact of glaciogenic cloud seeding on snowfall from orographic clouds. Weather Modification Association meeting, Santa Fe NM, 21 thru 23 April. (2) Geerts, B.: A series of progress reports presented at the Wyoming Cloud Seeding Pilot Project Advisory Team meetings in Cheyenne or Lander WY (May 07, Oct 07, Feb 08, Dec 08, Jul 09, and Dec 09).

Project 2008WY43B: A New Method for Tracing Seepage from CBNG Water Holding Ponds in the Powder River Basin, Wyoming. (1) Sharma S. and Baggett J. 2010. Role of stable isotopes in management of coalbed natural gas co-produced water. Goldschmidt 2010, June 13 thru 18, Knoxville, Tennessee. (2) Sharma S. 2010 Role of stable isotopes in water-energy research. ENVE5895 Environmental Engineering Seminar sponsored by Department of Civil and Architectural Engineering, University of Wyoming, 25 February 2010. (3) Sharma S. and Baggett J.K. 2010. A stable isotope approach for tracing seepage out of coalbed methane co-produced water holding ponds. Society of Range Management Annual meeting, Denver, February 7 thru 11. (4) Quillinan S., Frost C.D and Sharma S. 2009. Carbon isotope technique for coalbed aquifer characterization; Powder River Basin, Wyoming. Geological Society of America 2009 Meeting, Portland, October 18 thru 21. (5) Quillinan S. Frost C.D and Sharma S. 2009. Stable Isotope Techniques for Coalbed Aquifer Characterization; Powder River Basin, Wyoming. AAPG Annual 2009 Convention, Denver, June 7 thru 10.

Project 2008WY44B: Water Quality Criteria for Wyoming Livestock and Wildlife. (1) B. Wise, M. Raisbeck, 2009. Water quality for Wyoming Livestock and Wildlife. Rocky Mountain SETAC, Denver 4/23/09. (2) M. Raisbeck (2009) Water quality for Wyoming Livestock and Wildlife. Wyoming Water Law Conference, Cheyenne, WY, 4/23/09. (3) B. Wise, M. Raisbeck (2010) Water quality for Wyoming Livestock and Wildlife. 49th Annual Meeting of the Society of Toxicology, Salt Lake City, UT, 3/15/10. (4) B. Wise, M. Raisbeck (2010) Water quality for Wyoming Livestock and Wildlife. Rocky Mountain SETAC, Denver, CO, 4/16/10. (5) M. F. Raisbeck (2009): Water Quality for Livestock. Wyoming Livestock Roundup. 8/4/09. (6)

B. Wise and M. F. Raisbeck (2009): Water quality for livestock and wildlife. Wyoming Water Development Commission, Cheyenne, WY 11/21/09.

Project 2009WY46B: Detecting the signature of glaciogenic cloud seeding in orographic snowstorms in Wyoming II: Further airborne cloud radar and lidar measurements. (1) Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: Vertically-pointing airborne radar observations of the impact of glaciogenic cloud seeding on snowfall from orographic clouds. Weather Modification Association meeting, Santa Fe NM, April 21 thru 23. (2) Geerts, B.: A series of progress reports presented at the Wyoming Cloud Seeding Pilot Project Advisory Team meetings in Cheyenne (Dec 09) or in Lander WY (Jul 09).

Project 2009WY47B: Effects of Warm CBM Product Water Discharge on Winter Fluvial and Ice Processes in the Powder River Basin. (1) Kempema, E.W. and Ettema, R. November 2010. Progress Report to the Wyoming Water Development Commision, Cheyenne, WY. (2) Stiver, Jared, March 5, 2010. Effects of CBM waters in the Powder River Basin, invited presentation to RNEW 5710 class taught by Dr. KJ Reddy. (3) Kempema, E.W., Ettema, R, and Stiver, J. May 25, 2010. Effects of Coalbed Methane Product Water on Winter Flow in the Powder River; Energy Resources and Produced Waters Conference.

Project 2009WY48B: Characterization of Algal Blooms Affecting Wyoming Irrigation Infrastructure: Microbiological Groundwork for Effective Management. (1) Steven, B., and N. Ward. Deep sequencing of ribosomal RNA genes during an algal bloom in a eutrophic lake: a primer for metagenomic sequencing. DOE Joint Genome Institute 5th Annual User Meeting: Genomics of Energy & Environment. Walnut Creek, CA. March 24 thru 26, 2010. (2) Steven, B., S. McCann, K. H. Schulmeyer, and N. L. Ward. Characterization of the microbial diversity associated with algal blooms in a eutrophic freshwater lake. Abstract submitted to 13th International Symposium on Microbial Ecology. Seattle, WA. August 22 thru 27, 2010.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	6	0	0	0	6
Masters	8	0	0	3	11
Ph.D.	4	0	0	0	4
Post-Doc.	4	0	0	0	4
Total	22	0	0	3	25

Notable Awards and Achievements

Cover page of: Environmental Science and Technology, 43(23):2009. Image of fluorescently labeled tadpole courtesy of Paul E. Johnson, Project 2005WY24B, Real-Time Monitoring of E. Coli Contamination in Wyoming.

The following grants/fellowships were successful, in part, because of data and samples collected using WWDC/USGS funds: (1) Pribyl, P., NASA Space Grant Undergraduate Fellowship, 2009; (2) Pribyl, P., NSF EPSCoR Undergraduate Research Fellowship, Summer 2009; (3) Shuman, B, NSF Geography and Regional Sciences Program, CAREER: Effects of Prolonged Droughts, Severe Fires, and Forest Parasites on Regional Ecosystem Pattern in the Rocky Mountains Over the Past 5,000 Years, $480,273.

Publications from Prior Years

1. 2008WY45B ("Multi-Century Droughts in Wyoming's Past: Evidence of Prolonged Lake Drawdown") - Articles in Refereed Scientific Journals - Shuman, B., P. Pribyl, T. A. Minckley, and J.J. Shinker, 2010. Rapid hydrologic shifts and prolonged droughts in Rocky Mountain headwaters during the Holocene, Geophysical Research Letters 37: L06701. doi:10.1029/2009GL042196.
2. 2008WY45B ("Multi-Century Droughts in Wyoming's Past: Evidence of Prolonged Lake Drawdown") - Articles in Refereed Scientific Journals - Shinker, J. J., B. N. Shuman, T. Minckley, and A. Henderson, 2010. Climatic shifts in the availability of contested waters: a long-term perspective from the headwaters of the North Platte River, Annals of the Association of American Geographers, Forthcoming in October 2010 issue.